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Fracture Behavior in the Kinzel Test for Weldability

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FRACTURE BEHAVIOR IN THE KINZEL TEST FOR WELDABILITY

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INTRODUCTION

One of the properties of steel which makes it a highly useful engineering material is its relatively high ductility. In engineering structures this property is important since plastic yielding of highly stressed members may produce a more favorable distribution of stress within the structure. In addition the plastic yielding caused by overloading serves to give warning of impending failure. Unfortunately, steel does not always fail with prior plastic deformation, i.e. in a ductile manner. At reduced temperatures and under certain stress conditions steel structures can fail in a brittle manner, i.e. suddenly and with a minimum of plastic deformation. Such brittle fractures have occurred in welded ships, bridges, and pressure vessels as well as other structures.

The relative resistance of steels to brittle fracture is determined by a property called notch toughness. It is the purpose of this dissertation to report on the results of an investigation designed to study critically one of the tests used to determine the effect of welding on notch toughness.

Notch Toughness and the Effect of Welding

The amount of energy required to cause rupture of a material is a measure of its toughness. Since most specimens used to measure the toughness of steels contain artificial notches the behavior of steels in these tests is indicative of their notch toughness. Aside from metallurgical variables of testing three factors have a pronounced influence on the notch toughness of steel. These factors are the temperature of testing, the rate of loading, and the specimen geometry including notch severity. In testing for notch toughness the geometry and rate of loading are usually held constant and the temperature of testing is varied. Curves of energy absorbed during testing vs. test temperature are characterized by a relatively sharp drop in energy absorbed as the temperature is lowered. The temperature range over which this sharp drop occurs is termed the transition temperature range and the behavior of specimens is said to change from ductile to brittle. Examination of fractured specimens reveals a change from fibrous to crystalline appearance in this range. This is a result of a change in the mode of fracture from shear to cleavage as the temperature is lowered.

The transition temperature is a fundamental property of steels and is used to compare the notch toughness of steels. It is important to note, however, that the transition temperature obtained from any one test is specific to that test, and results from one type of test specimen cannot be compared directly to results from a different test specimen. Further, the results of laboratory notch toughness tests cannot be translated directly for use as a criterion for service performance.

The test most used for the evaluation of the effect of welding on notch toughness is the notch-bend test. By means of this test the notch toughness of specimens containing welds are compared with the notch toughness of unwelded specimens. It is usually found that welding severely impairs the performance of such specimens, resulting in a shift of the transition temperature to higher temperatures.

The Notch Bend Test

The longitudinal-bead-weld notch-bend test has been extensively used to evaluate the notch toughness of welded steels. Of the several designs for specimens of this type the design proposed by Kinzel and associates[1,2,3] has become widely accepted. The details of the test specimen as used in the present investigation are shown in Figure 1. A single weld bead is deposited longitudinally on the surface of the plate using any desired welding conditions. After welding, transverse notches (0.05 inch depth, 0.01 inch radius, 45^{o} vertex angle) are machined into the specimen. Suitable post-weld treatments can, of course, precede notching. Each notch exposes at its root surface weld metal, heat-affected base metal and unaffected base plate as shown in Figure 2. The specimen is tested in bending as shown in Figure 3. As a result of this bending and the position of the notch, failure can originate in the most sensitive structure.

The manner in which the Kinzel test specimen fails is temperature sensitive; i.e. the test behaves like other notch toughness tests such as the V-notch Charpy impact test and the notch-tension test in that at sufficiently high temperatures failure occurs by shear with appreciable plastic deformation while at sufficiently low temperatures failure is by cleavage with negligible plastic deformation. Specimens tested over a range of temperatures exhibit, therefore, a transition from ductile behavior (shear failure) to brittle behavior (cleavage failure). It is the measurement of this transition temperature which is of importance in the Kinzel type test.

Various criteria may be used to measure the behavior of individual specimens when tested. Among these are ductility, energy absorbed, and appearance and mode of fracture. Since lateral contraction appears to be a reliable index of ductility and since its measurement is easy to carry out, its use has become widespread. Lateral contraction is obtained by measuring, at a point 1/32 inch below the root of the notch, the width of the specimen before and after testing. The lateral contraction of each specimen is then reported as a percentage. For any one series of specimens the transition from ductile to brittle behavior can be determined by plotting the per cent lateral contraction vs. testing temperature. Such a curve is shown schematically in Figure 4. It is common practice to designate as the transition temperature that temperature at which 1% lateral contraction is obtained. This is termed the ductility-transition temperature and usually occurs when the tested specimens fail in an almost completely brittle manner. This choice of transition temperature at a relatively low point on the transition curve is a result of studies which have shown that practically all service failures have occurred with almost no manifestations of ductility. Furthermore, a relatively low level of performance in the Charpy impact test (10 ft.-lb.) correlates with the susceptibility of ship plates to brittle fracture in service(4).

The use of the Kinzel type test for the evaluation of the notch toughness of welded steel is a result primarily of its sensitivity to such variables as the thickness, composition and mechanical and thermal history of the steel, and the conditions of welding including heat input, preheating, and postheating. However, when these known factors are taken into consideration the transition temperatures of welded steels will exhibit a scatter of 75 to 100°F. It is therefore difficult to predict except in a more or less general way the effect on transition temperature of changing any of the above variables. The author believes that this situation is partially a result of lack of knowledge concerning the mechanics of failure in the Kinzel type test.

The purpose of the present investigation in the broad sense was to study the Kinzel type test in order to determine factors which govern brittle behavior in welded steel. In particular the problem resolved itself into a study of the effect of weld metal, heat-affected-zone, and unaffected base plate in the initiation and propagation of the crack leading to brittle failure in the Kinzel test. Questions to be answered included: (1) In what areas do cracks initially form? (2) When and where do such cracks become critical? (3) What are the properties of the various regions in the welded zone and what is the effect of these properties on crack initiation and propagation? (4) How are the preceding factors related to the shape and position of the transition curve?

Previous work concerning fracture initiation and propagation leading to brittle failure in the notch slow bend test is meager. Stout and McGeady[5,6] have demonstrated that initial cracking appears in either prime or welded plate at relatively small angles of bend. When welded with E6010 electrodes in steels containing about 0.18% C and no alloys the first crack was found to appear in the weld metal. In steels of higher alloy or carbon content (0.25% C) the initial crack was found to form in the heated zone of the base plate. Voldrich and co-workers[7] showed that in Kinzel-type specimens of two steels (0.18 and 0.24% C) welded with E6010 electrodes, fractures initiated and propagated first in weld metal. They concluded that the behavior of the welded specimens was controlled primarily by cracking of the weld metal.

Nippes and Savage[8] have investigated the properties of synthetically produced weld heat-affected-zone structures using Charpy V-notch impact specimens. The steel used was a 0.16% C Grade A-201 steel and the structures investigated corresponded to those produced in 1/2 inch plate welded with a heat input of 70,000 joules per inch. Their results showed that in this steel the structures produced by heating below the lower critical temperature developed the poorest notch toughness. Unfortunately no attempt was made to relate these properties to the behavior of welded specimens.

Granjon and Videau[9] have observed interesting fracture patterns on the fractured surfaces of Kinzel specimens. In certain temperature ranges these specimens showed almost 100% crystalline appearance except for a thin, fibrous semi-circle surrounding the heat-affected-zone but well below it.

EXPERIMENTAL PROCEDURE

Materials

Steels chosen for this investigation were ordered to A.S.T.M. specifications. Analyses are given in Table I.

TABLE I

Chemical Composition of Steels

Steel	Thickness	C	Mn	P	S	Si	Mo	Ni	Cr
A-201	1"	.11	.51	.020	.024	.20	.01	.01	.01
A-7	1"	.32	.74	.013	.039	.08	.02	.04	.03
A-302	1"	.18	1.12	.035	.033	.23	.45	.06	.03
A-302	½"	.18	1.12	.035	.034	.20	.41	.06	.03

Photomicrographs of these steels in the as-received condition are presented in Figure 5. Test specimens were removed from the as-received plates in a predetermined random pattern.

Electrodes 3/16 inch in diameter were ordered to AWS specifications. The type and nature of electrodes used is shown in Table II.

TABLE II

Type and Nature of Electrodes

Type	Coating	Hydrogen Contact
E6010	cellulose	high
E7015	lime	low
E9010	cellulose	high

Specimen Preparation

Kinzel specimens were cut from the as-received plate according to the specifications shown in Figure 1. The surface to be welded was ground to remove all scale. Welding of the single longitudinal bead on plate was accomplished using 180 amps. and 28 arc volts for E6010 and E9010 electrodes and 210 amps. and 22 arc volts for E7015 electrodes. Except for one series the arc travel was held constant at 6 inches per minute. If postheating was to be done, this followed welding immediately and was accomplished by holding specimens for one hour at 1150°F. All specimens were held 7 days after welding before testing.

Specimens for standard V-notch Charpy impact tests were taken from the plate with the longitudinal axis of the specimen parallel to the rolling direction. The notches in these specimens were located perpendicular to the plate surface. Specimens to be heat treated were machined approximately 0.035 inch oversize in order to allow for oxidation or decarburization of the surface during heating. After heat treatment these specimens were ground to standard dimensions and then notched.

Production of synthetic weld zone microstructures in Charpy specimens was accomplished by heating specimens to carefully chosen temperatures and then cooling in a medium selected to produce a cooling rate approximating that developed in the heat-affected-zone of the Kinzel specimens when welded. Heat treatment temperatures were chosen for each steel after careful metallographic and visual analysis of fracture patterns of Kinzel test specimens. Heating of specimens to 1700°F and below was accomplished in molten lead baths. Total heating time in lead was two minutes. Above 1700°F a high temperature glo-bar furnace with a gas-air protective atmosphere was employed for heating. Total heating time here was 3 minutes.

All specimens were still-mineral oil quenched after heating. As will be shown later microstructures produced by cooling in this way were similar to those developed in the heat-affected-zones of Kinzel specimens of the various steels. Since the welding heat input was essentially constant for all Kinzel specimens only one cooling rate was needed.

<u>Testing Procedure</u>

Testing of Kinzel specimens was accomplished as shown in Figure 3 on a 120,000 lb. hydraulic testing machine. Head travel speed was held constant at 2 inches per minute. In addition to final percentage lateral contraction a load-deflection curve was obtained for each specimen. This curve was traced by means of an automatic stress-strain recorder utilizing a microformer deflectometer placed to measure the movement of the testing machine crosshead. Load-deflection curves were used to obtain values of deflection at both initial and final failure.

V-notch Charpy specimens were tested through the transition range in order to obtain the 10 ft.-lb. transition temperature.

Illustration of Fracture Patterns

Careful examination of the fracture surfaces of all Kinzel specimens was performed after testing. Since these fracture surfaces revealed interesting patterns of fibrous and crystalline appearance which were indicative of specimen behavior during testing, it was decided to record each fracture pattern. Figure 6 is a photograph of a typical Kinzel specimen fracture surface. Areas of fibrous and crystalline fracture are clearly visible in this photograph. Unfortunately it was difficult to show clearly by photographs many of the fracture patterns and for this reason it was decided to use drawings to illustrate fracture appearance.

Figure 7 is a drawing illustrating the fracture pattern of Figure 6. The root of the notch is represented by the top horizontal line while the fusion line of the weld metal is shown by the semi-circular dashed line. Areas of fibrous fracture (ductile behavior) are indicated by cross-hatching, while areas of crystalline fracture (brittle behavior) are open. The percentage lateral contraction for each specimen is indicated in the corner. Testing temperature is noted at the side. It will be noticed that the fibrous area in the lower quarter of Figure 6 has been omitted in Figure 7. This is done for two reasons. First, the specimens are considered to have failed when the load drops to one-half the maximum load. Failure in the lower quarter of the specimen is therefore usually obtained when separating the two halves of the specimen after the actual testing has been completed. Second, the mode of failure in this region will not affect the percentage lateral contraction.

Transition Behavior as Shown by Deflection

It became apparent from examination of fracture patterns on Kinzel specimens that the final percentage lateral contraction at failure did not give complete information concerning the temperature of initiation and propagation of cleavage failure. This was the case when an initial cleavage crack was not able to propagate through the specimen but was forced to change to shear by either the heat-affected-zone or the base material. In such cases the percentage lateral contraction at the time of initiation of cleavage failure as well as the final percentage lateral contraction would be of interest. Since continuous measurements of lateral contraction during testing are not practical, automatic measurements of deflection were used instead. Figure 8 illustrates, schematically, how load-deflection diagrams were used to obtain values of deflection at both initial cleavage failure and final failure of Kinzel specimens. Figure 8a represents the behavior of a specimen which fails completely by cleavage once a cleavage crack is initiated. Figure 8b represents the behavior of a specimen in which the initial cleavage crack is stopped and changed to shear somewhere within the specimen. After additional loading, cleavage is once again initiated and final failure occurs. In Figure 8c, after the cleavage crack has been stopped, final failure occurs completely by shear. In this case the specimen is assumed to have failed when the load drops to one-half the maximum load. Transition curves were obtained by plotting deflection at both initial brittle failure and final failure against testing temperature.

RESULTS AND DISCUSSION - A-302 STEEL

1" A-302 Steel

The transition curves for the 1 inch thick A-302 steel as received, as welded, and as welded and post-heated are presented in Figure 9. Specimens were welded with E9010 electrodes at 70°F. The 1% lateral contraction transition temperatures taken from these curves are:

As received	:	-110°F
Welded	:	+120°F
Welded and Postheated	:	0°F

As can be seen, welding severely impairs the notch toughness of the steel effecting a rise in transition temperature of 230°F. Postheating greatly improves the notch toughness of the welded specimens but the notch toughness is still considerably below that of the unwelded specimens.

Figures 10, 11, and 12 illustrate the variation in fracture pattern through the transition range for the three conditions. The fracture behavior of the unwelded series in Figure 10 is straightforward. As the temperature rises a thin shear lip develops over the width of the specimen at the root of the notch. This shear lip increases in depth with increasing temperature. Increasing values of lateral contraction are therefore associated with increasing amounts of shear at the notch root.

The fracture behavior of the welded series as shown in Figure 11 is relatively complex. With increasing temperature this behavior can be described as follows:

+70°F - The weld metal and a portion of the heat affected zone have failed by shear. Brittle fracture was initiated somewhere within the heat-affected-zone and the remainder of the specimen failed by cleavage.

+110°F - Weld metal and most of H.A.Z.* have failed by shear. Brittle fracture was initiated within H.A.Z.

+120°F - Same as 110°F. Lateral contraction below 1%.

+130°F - Weld metal and most of H.A.Z. have failed by shear. Brittle fracture initiated within H.A.Z. Propagation of cleavage crack, however, has been prevented by an apparently tougher microstructure which fails by shear until the crack has been sufficiently resharpened to cause remainder of specimen to fail brittlely. A thin ring of crystalline fracture is visible in H.A.Z. A sharp rise in lateral contraction above 1% is observed.

+140°F - Same as 130°F except for increasing base metal shear due to increased temperature.

The welded and postheated series shows in Figure 12 the following behavior:

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*Here and in the remainder of the text "heat-affected-zone" is abbreviated "H.A.Z."

$-50^{\circ}F$ - Entire specimen failed by cleavage. Point of initiation of failure not possible to detect.

$-30^{\circ}F$ - Slight shear lip visible in weld metal. Initiation of brittle fracture apparently occurs in weld metal.

$-10^{\circ}F$ - Same as $-30^{\circ}F$ except that the amount of weld metal shear has increased.

$0^{\circ}F$ - Lateral contraction rises considerably above 1% due to shear failure over width of specimen and considerably below fusion line. Weld metal is 100% shear.

$+10$ & $20^{\circ}F$ - Same as $0^{\circ}F$ with increasing extent of base metal shear.

Plots of permanent specimen deflection vs. temperature at initial brittle failure and final failure for the two welded series are shown in Figure 13. It is to be noticed that for the as welded series there is a definite separation between deflection at brittle fracture initiation and at final failure. Furthermore, initiation of cleavage failure occurs at approximately the same deflection over a wide temperature range indicating that a specific structure in the H.A.Z. is responsible for this behavior.

The behavior of the as welded series can be summarized as follows: Below 1% lateral contraction the H.A.Z. fails in shear down to a specific point at which cleavage failure is initiated and propagates through the remainder of the specimen. Lateral contraction rises above 1% due to the fact that the initial cleavage crack is stopped and failure by shear once more begins. Three areas of the H.A.Z. thus appear to influence the behavior of the specimen: (1) the coarse-grained region which fails in shear, (2) the area which initiates and propagates cleavage failure, and (3) the area which at sufficiently high temperatures stops propagation of this cleavage crack.

In order to determine microstructurally the location of these areas in the H.A.Z., the fracture surface of a specimen corresponding to the one tested at +130°F (Figure 11) was nickel plated and then sectioned at the centerline of the weld. The resulting surface perpendicular to the fracture surface was then polished and etched to allow microexamination of the fracture surface profile. Areas of the H.A.Z. which had failed by shear were characterized by an irregular profile while areas which had failed by cleavage were characterized by sharp well defined facets. Examination of this specimen revealed that the H.A.Z. could be divided into three distinct areas:

1. The region heated above the upper critical temperature which was essentially martensitic and which failed by shear.

2. The region heated between the lower and upper critical temperatures which was mixed martensite and ferrite

and which failed by cleavage.

3. The region heated to temperatures below the lower critical which was pearlite plus ferrite and which failed by shear.

Initiation of cleavage failure occurred in the region heated just below the upper critical temperature where a mixture of martensite and ferrite was present. The cleavage crack propagated through this region but was stopped by the apparently tougher region heated below the lower critical temperature.

V-notch Charpy specimens with microstructures simulating those of the above defined H.A.Z. regions were prepared by heating to 2200°F, 1450°F and 1320°F. These microstructures and their hardnesses are compared in Figure 14. V-notch Charpy transition curves for these microstructures and as received material are presented in Figure 15. Curves for specimens heat treated at 1450 and 2200°F and then post-heated at 1150°F are also presented. These results are summarized in Table III, using the 10 ft.-lb. level as the transition temperature.

TABLE III

Charpy 10 ft.-lb. Transition Temperatures for Synthetic H.A.Z. Structures of A-302 Steel

Heat Treatment	Microstructure	Transition Temp. °F
As received	Ferrite & Pearlite	+10°F
1320°F	Ferrite & Pearlite	-10°F
1450°F	Martensite & Ferrite	+130°F
2200°F	Martensite	-45°F
1450°F & P.H.	Tempered Martensite and Ferrite	-120°F
2200°F & P.H.	Tempered Martensite	-200°F

It is evident from these data that the martensite and ferrite structure which is most susceptible to cleavage failure in the Kinzel test exhibits the poorest notch toughness as revealed by the Charpy V-notch impact test. Furthermore, the martensitic structure has notch toughness superior to both the unheated base plate and the material heated to just below the lower critical temperature. These results are clearly in agreement with observations of the as welded Kinzel specimen fracture patterns in Figure 11.

Postheating at 1150°F substantially improves the notch toughness of specimens heat treated at 1450 and 2200°F. This improvement in notch toughness is reflected by an improvement in the Kinzel test transition temperature from +120°F, as welded, to -10°F welded and postheated. Referring to the fracture behavior of this series in Figure 12 it is seen that the lateral contraction rises above 1 per cent at 0°F when the H.A.Z. is able to fail by shear as a result of the improvement in notch toughness due to postheating. The drop in lateral contraction below 1 per cent at -10°F is apparently due to the ability of the weld metal to initiate cleavage failure. Once initiated, the cleavage crack is able to propagate through the relatively tough heat affected zone. These results indicate that although postheating produces structures in the critical areas of the H.A.Z. which have notch toughness superior to that of the base metal a similar improvement in the notch toughness of the weld metal may not result. The properties of the weld metal may, therefore, limit the improvement in Kinzel test transition temperature due to postheating.

1/2" A-302 Steel

An interesting supplement to the fracture study of the 1 inch thick A-302 steel was provided through examination of the fracture behavior of welded Kinzel specimens of 1/2 inch thick A-302 steel. Both the 1/2 inch and 1 inch A-302 plates were rolled from the same heat of steel and as Table I indicates their analyses are almost identical. Despite this similarity in analysis, comparison of the fracture behavior of the 1/2 inch and 1 inch specimens when welded with E9010 electrodes showed a surprising difference. As has been shown, initiation of cleavage failure in 1 inch thick specimens occurred most easily in the intercritically heated region of the H.A.Z. while the coarse grains of the H.A.Z. failed by shear. In the 1/2 inch thick specimens, however, initiation of cleavage failure occurred most easily in the coarse grains of the H.A.Z. Metallographic examination of the H.A.Z. of the welded 1/2 inch specimens revealed that the coarse-grained region consisted of pearlite and ferrite. This is in contrast to the martensitic structure of the coarse-grained region in the 1 inch thick specimens. These microstructures are compared in

Figure 16.

The difference in H.A.Z. microstructures is explained if it is realized that the weld zone cooling rates are much faster in the 1 inch thick specimens than in the 1/2 inch thick specimens due to the fact that the heat input per unit volume of metal in the 1/2 inch specimens is twice that in the 1 inch specimens. In order to study further the effect of heat input on fracture behavior, a series of 1/2 inch thick specimens were welded with E9010 electrodes at a travel speed of 12 inches per minute instead of the standard speed of 6 inches per minute. This reduced the heat input by one-half, thus making it comparable to that produced in 1 inch thick specimens welded at 6 inches per minute. The fracture behavior of the 1/2 inch A-302 steel welded at both 6 and 12 inches per minute is shown in Figure 17. Comparison of these two series reveals the following:

1. In the specimens welded at 6 inches per minute the coarse grains of the H.A.Z. are responsible for initiation of cleavage failure.

2. The specimens welded at 12 inches per minute behave like those of the 1 inch plate in Figure 10 in that at sufficiently high temperatures the coarse grains fail by shear and cleavage is initiated within the intercritical region of the H.A.Z.

3. Despite the difference in fracture behavior the transition temperatures of the two series are approximately the same; $+90^{o}F$ at 6 inches per minute and $+100^{o}F$ at 12 inches per minute.

4. The fact that there is little difference in transition temperature is apparently due to the controlling influence of the base material. For both series of specimens the rise in lateral contraction above 1% is due to the ability of the base material to prevent easy propagation of a cleavage crack.

CONCLUSIONS - A-302 STEEL

1. Welding decreases the notch toughness of Kinzel specimens by providing a structure within the heat-affected-zone which can initiate cleavage failure more readily than can the base material itself. In the 1 inch A-302 steel welded at 6"/minute and the 1/2 inch A-302 steel welded at 12"/minute, this structure consists of mixed martensite and ferrite, which is formed when the base metal is heated within the intercritical region. In the 1/2 inch A-302 welded at 6"/minute this structure is ferrite and pearlite in the coarse grains of the H.A.Z.
2. The amount of decrease in notch toughness due to welding is limited by the ability of the base material or a subcritically heated portion of the H.A.Z. to resist propagation of a cleavage crack when sufficiently high testing temperatures are reached.
3. Postheating improves the notch toughness of welded specimens by increasing the notch toughness of the intercritically heated structure, thus eliminating it as a site for cleavage crack initiation.
4. The extent of improvement in notch toughness due to postheating is limited by the notch toughness of the weld metal, since in postheated specimens cleavage is initiated within the weld metal.

RESULTS AND DISCUSSION, A-7 STEEL

The Kinzel test transition curves for the A-7 steel unwelded and in three welded conditions are shown in Figure 18. It is to be noticed that two of these curves exhibit a pronounced plateau over a range of temperatures near the 1 per cent level, making it difficult to choose the transition temperature with any accuracy. If, for these curves, the mid-temperature of the plateau is chosen as the transition temperature, comparative transition temperatures are those listed in Table IV.

TABLE IV

Kinzel Test Transition Temperatures for A-7 Steel

Condition	Transition Temperature, $^{\circ}F$
Unwelded	-85
Welded E6010	+60
Welded E7015	+60
Welded E6010 and Postheated	+45

It is evident that welding severely impairs the notch toughness of the A-7 steel. There is little difference in notch toughness between specimens welded with E6010 and low hydrogen E7015 electrodes and postheating the E6010 series effects only a slight improvement in notch toughness.

Fracture behavior of Kinzel specimens, through the transition region, for the three welded series is illustrated in Figures 19 through 21. Fracture behavior of the unwelded series is similar to that of the A-302 steel shown in Figure 10. The fracture behavior of the welded E6010 series as shown in Figure 19 can be described as follows:

40 & 50°F -	Entire specimen including weld metal fails by cleavage. Lateral contraction very low. The site of brittle fracture initiation not possible to detect.
50 & 60°F -	Weld metal and H.A.Z. fail by cleavage. Initial cleavage crack changes to shear in base material producing a ring of fibrous appearance. Remainder of specimen fails by cleavage when shear crack is resharpened as the load on specimen builds up again. Lateral contraction rises sharply to .9%.
70°F -	Two fibrous rings result when base plate increases its resistance to cleavage crack propagation. Lateral contraction rises to 1.5% due to second fibrous ring.
90°F -	Weld metal shows slight shear lip. Cleavage is initiated either in weld metal or coarse-grained region of H.A.Z. Fibrous rings have grown in breadth causing rise in lateral contraction to 2.0%.
145°F -	Weld metal has failed entirely by shear. Brittle fracture is initiated in coarse grains of H.A.Z. Propagation of cleavage crack is limited.

160°F - Cleavage initiated in coarse grains of H.A.Z. and propagates through H.A.Z. only. Remainder of specimen is fibrous.

The fracture behavior of the E7015 series as shown in Figure 20 is similar to that of the E6010 series and will not be described in detail. It is to be noted, however, that the E7015 weld metal is somewhat tougher than the E6010, since it is completely fibrous at 80°F, while the E6010 weld metal does not fail completely by shear until temperatures above 90°F are reached.

The fracture behavior of the series welded with E6010 electrodes and then postheated is illustrated in Figure 21 and can be described as follows:

40°F - Weld metal has slight shear lip. Cleavage failure apparently initiated in weld metal and remainder of specimen fails by cleavage.

50°F - Quantity of weld metal shear has increased somewhat but cleavage failure still initiated by weld metal.

50°F - Cleavage failure initiated by weld metal. Thin fibrous ring within or just below H.A.Z. is formed when further propagation of cleavage crack is prevented. Shear failure in this region causes a rise in lateral contraction to 1.1%.

60°F - Same as above.

60°F - Weld metal is 100% fibrous. Shear failure includes H.A.Z. Lateral contraction increases to well above 1%.

$70^\circ F$ — Same as $60^\circ F$.

The behavior of the two as welded series may be summarized as follows: Cleavage failure is initiated by either weld metal or the coarse-grained region of the H.A.Z. At relatively low temperatures initiation probably occurs in the weld metal while at higher temperatures the coarse-grained region is responsible for initiation. It appears, therefore, that the coarse-grained structure of the H.A.Z. is critical to the behavior of the specimen since it can initiate cleavage failure when the weld metal is unable to do so. Thus even if a tougher weld metal were introduced it is doubtful that much improvement in the Kinzel test transition temperature would be effected. The rise in lateral contraction to 1 per cent is a result of the ability of the base metal to prevent the propagation of a cleavage crack when sufficiently high temperatures are reached and the lateral contraction rises above 1 per cent with increasing amounts of base metal shear.

In Figure 22 specimen deflection at initial brittle fracture and at final specimen failure are plotted against testing temperature for the Kinzel specimens welded with E6010 electrodes and not postheated. This plot shows that the initiation of brittle fracture occurs at approximately the same value of specimen deflection. This is true despite the fact that as temperature increases the amount of weld metal shear occurring prior to the initiation of cleavage failure increases, becoming 100% between 90 and 145°F. It is apparent, therefore, that the manner in which the weld metal fails influences only slightly the specimen deflection at final failure and thus can not be expected to influence lateral contraction to any extent. In the unpostheated specimens, therefore, the mode of weld metal failure does not affect the Kinzel test transition temperature.

As revealed in Figure 21 postheating improves the toughness of the coarse grains of the H.A.Z. markedly. The fact that only a slight improvement in transition temperature resulted is apparently due to the ability of the weld metal to initiate cleavage failure at sufficiently low temperatures. The rise in lateral contraction to and above 1 per cent occurs either when a structure within the H.A.Z. can prevent propagation of a weld metal initiated cleavage crack or when the weld metal fails completely by shear and thus is unable to initiate cleavage failure.

Since within the H.A.Z. the coarse-grained structure, i.e. the structure just below the fusion line of the weld metal, is responsible for the initiation of cleavage failure in the as welded specimens, Charpy V-notch specimens with a microstructure simulating that observed in this region were prepared by heating to 2200°F and still mineral oil quenching. An additional series was postheated after the above treatment to produce a structure simulating that observed in the welded and postheated series. These microstructures together with hardnesses are compared in Figure 23. V-notch Charpy transition curves for the synthetic structures and for the as received material are presented in Figure 24. The 10 ft.-lb. transition temperatures from these curves are:

As received	+55°F
2200°F	+180°F
2200°F, Postheated	-50°F

The coarse-grained region of the H.A.Z. of the as welded specimens consists of large grains of martensite surrounded by a very fine pearlite associated with the prior austenite grain boundaries. Some ferrite is also visible at these boundaries. As might be expected this structure exhibits extremely poor notch toughness as revealed by synthetic V-notch Charpy specimens. The 10 ft.-lb. transition temperature is +180°F and examination of the transition curve reveals it to be extremely flat with an energy absorption of less than 15 ft.-lbs. at 360°F despite the fact that at this temperature failure is 100 per cent by shear. The poor notch toughness of this structure is in agreement with the previously discussed fracture behavior of as welded specimens, since it was shown then that the coarse-grained region was responsible for the initiation of cleavage failure even at relatively high temperatures.

Postheating of the martensite-pearlite coarse-grained structure produces a marked change in microstructure as revealed in Figure 23. The martensite is tempered, of course, and now consists of carbide in a ferrite matrix. However, the surprising change is the complete spheroidization of the pearlite. As might be expected this structure has a relatively good transition temperatures of -50°F as compared to +180°F for the unpostheated specimens. This improvement in notch toughness supports the observed fracture behavior of welded and postheated Kinzel specimens in Figure 21 where it was seen that at the test temperature employed this structure could not initiate cleavage failure. Apparently, however, this structure is capable of propagating a cleavage crack initiated by the weld metal.

CONCLUSIONS - A-7 STEEL

1. Welding decreases the notch toughness of Kinzel specimens of the A-7 steel by providing a structure within the heat-affected-zone which can initiate cleavage more readily than the base material itself. In this steel this structure consists of mixed martensite and pearlite with some ferrite. This is in the coarse-grained region of the H.A.Z.
2. The amount of decrease in notch toughness due to welding is limited by the ability of the base material to prevent cleavage crack propagation at sufficiently high testing temperatures. Relatively tough areas within the H.A.Z. may also contribute to this effect.
3. Welding with E6010 and E7015 low hydrogen electrodes produced no difference in transition temperature and essentially no difference in fracture behavior. Fracture behavior did, however, reveal that the E7015 weld metal was somewhat tougher than the E6010 weld metal.
4. Postheating produced a slight improvement in notch toughness. The improvement was due to an increase in notch toughness of the coarse grains of the H.A.Z., i.e. the structure responsible for initiation of cleavage in unpostheated specimens.

5. The fact that the improvement due to postheating was only slight is apparently a result of the ability of the weld metal to initiate cleavage in these specimens. In other words, postheating did not improve the properties of the weld metal as much as those of the H.A.Z. and therefore the weld metal limited the effectiveness of postheating.

RESULTS AND DISCUSSION - A-201 STEEL

Kinzel test transition curves for the A-201 steel unwelded and in three welded conditions are presented in Figure 25. The 1% lateral contraction transition temperatures taken from these curves are tabulated in Table V.

TABLE V

Kinzel Test Transition Temperatures for A-201 Steel

Condition	Transition Temperature °F
As received	-120
Welded E6010	+20
Welded E7015	+20
Welded E6010 and Postheated	-55

As can be seen, welding severely impairs the notch toughness of the A-201 steel since the transition temperature rises from -120°F unwelded to +20°F as welded. The transition curves for specimens welded with E6010 and E7015 electrodes and not postheated are almost identical and both give a transition temperature of +20°F. Postheat applied to the E6010 specimens improves notch toughness by lowering the transition temperature from +20°F to -55°F.

Fracture behavior of Kinzel test specimens through the transition range for the three welded series is illustrated in Figures 26 through 28. Fracture behavior of the unwelded specimens is similar to that previously described for the A-302 steel.

The fracture behavior of the E6010 unpostheated series as illustrated in Figure 26 can be described as follows:

-50°F	-	Entire specimen, including weld metal fails by cleavage.
+10°F	-	Slight shear lip visible in weld metal. Remainder of specimen fails by cleavage. Lateral contraction rises from 0.3% at -50 to 0.6% apparently due to partial shear failure of weld metal.
+20°F	-	Slight shear lip in weld metal. Cleavage crack which is initiated by either the weld metal or coarse grains of the H.A.Z. is changed to shear by a structure within the H.A.Z. Upon continued loading cleavage is once again initiated. As a result a thin fibrous ring is visible within the H.A.Z. The shear occurring in this region raises the lateral contraction to 1.1%.
+20°F	-	Behavior is similar to that described just above except that an additional fibrous ring well down in base metal is now visible. Base metal is apparently unable to propagate cleavage crack easily at this temperature.
+30°F	-	Although the drawing indicates that the weld metal of this specimen has failed entirely by shear, it is possible that a

small portion close to the fusion line failed by cleavage. It is difficult to say, therefore, whether the weld metal or the coarse grains of the H.A.Z. had initiated cleavage failure. Once initiated, however, the cleavage crack propagated to a structure within the H.A.Z. where it was changed to shear. Extensive shearing then occurred in the base metal of the specimen. This caused a marked rise in lateral contraction.

+40°F - Same as +30°F except for increased base metal shear.

+50°F - (Not Shown) Entire specimen, including H.A.Z. failed by shear.

The fracture behavior of specimens welded with E7015 electrodes is shown in Figure 27 and can be described as follows:

-50°F - Same as E6010 specimen.

+10°F - Same as E6010 specimen.

+20°F - Weld metal appears to be 100% shear. However, as was observed previously it was difficult to determine whether or not cleavage did occur in the weld metal near the fusion line. The site of initiation of the cleavage failure is therefore in doubt and could possibly be in the weld metal, at the fusion line, or in the coarse grains of the H.A.Z. Cleavage, once initiated, propagates through entire specimen.

+20°F - In this specimen the weld metal fails completely by shear. The shear crack grows through the H.A.Z. and over the width of the specimen until well within the base plate where cleavage failure begins. The lateral contraction rises from 0.7% in the previous specimen to 2.2% in this specimen.

+30°F - Same as +20 with increasing base metal shear.

+40°F - Same as +30°F.

As shown in Figure 28, the fracture behavior of the E6010 welded and postheated series is very similar to that of the E7015 series except that testing temperatures are lower. Therefore this series will not be discussed in detail.

Several aspects of previously discussed fracture behaviors deserve special attention. Comparison of the fracture behaviors of specimens welded with E6010 and E7015 electrodes and not postheated reveals a striking difference despite the fact that their transition temperatures are almost identical. In the E6010 specimens the weld zone is able to initiate cleavage failure at higher temperatures than in the E7015 specimens. This can be explained in two ways; first by assuming that the weld metal initiates cleavage failure and second by assuming that the coarse-grained structure in the H.A.Z. initiates cleavage failure. Support for the first possibility is obtained by comparison of Figures 26 and 27 where it is seen that the E7015 weld metal is tougher than the E6010 weld metal since it attains nearly 100% fibrous behavior at +20°F, while the E6010 weld metal does so at +30°F. However, if the weld metal is the cleavage crack initiator, then definite traces of cleavage behavior extending from the weld metal across the fusion line and into the H.A.Z. should have been evident in the +40°F specimen in Figure 26 and the +20°F specimen in Figure 27. Unfortunately, since the carbon contents of the weld metal and H.A.Z. of this steel are about the same, it was difficult to detect the position of the fusion line in these specimens. Thus the presence or absence of cleavage facets in the weld metal at the fusion line was difficult to ascertain with certainty.

If the weld metal of the specimens discussed above does fail completely by shear, then the coarse-grained region of the H.A.Z. must be responsible for initiation of cleavage failure. In this case, hydrogen embrittlement might account for the poorer notch toughness exhibited by the coarse grains of the specimens welded with E6010 electrodes, since these electrodes produce considerable hydrogen during welding while the opposite is true of the E7015 electrodes.

On the basis of the above explanations of the origin of brittle fracture, the beneficial effect derived from postheating of the E6010 Kinzel specimens must be due to an improvement in toughness of either the weld metal or the H.A.Z.

A third possible site for the initiation of cleavage failure is at the fusion line where microstructural discontinuities may exist. Postheating might act to reduce their magnitude, thus increasing the toughness.

In order to determine the properties of the coarse-grained region of the H.A.Z., V-notch Charpy specimens were heated to 2200°F and still mineral oil quenched to reproduce this structure synthetically. One set was tested as quenched and one quenched and postheated at 1150°F. Transition curves for the as received A-201 material and for the two synthetic structures are presented in Figure 29. The 10 ft.-lb. transition temperatures from these curves are:

As received	+10°F
2200°F	+5°F
2200°F, Postheated	+5°F

Comparison of these results reveals little difference in toughness between the as received material and the two synthetic structures. Since no improvement resulted from postheating, these data would seem to indicate that the weld metal rather than the coarse grains of the H.A.Z. are responsible for the initiation of brittle failure.

The fact that hydrogen was not introduced into the synthetic specimens does not invalidate this supposition since it is to be expected that postheating would improve the toughness of Kinzel specimens welded with low hydrogen E7015 electrodes as it did for E6010 Kinzel specimens.

Despite the fact that in the E6010 welded Kinzel specimens the weld zone is able to initiate cleavage failure at higher temperatures than in the E7015 specimens, the E6010 Kinzel specimens exhibit notch toughness equal to the E7015 Kinzel specimens. This is due to the ability of both the base material and an area within the H.A.Z. to prevent easy propagation of a cleavage crack at sufficiently high temperatures. Thus in the E6010 Kinzel specimens shearing within the H.A.Z. and base material causes the lateral contraction to rise to and above 1%.

The fibrous ring caused by shearing within the H.A.Z. is shown clearly in the +20°F specimens in Figure 26. The position of this ring was determined by nickel plating the fracture surface of a specimen containing this ring, sectioning it at the weld centerline, and examining the fracture profile metallographically. This examination revealed that the initial cleavage crack was stopped by the region heated only slightly above the upper critical temperature during welding and which, therefore, possessed a refined microstructure. Cleavage was once again initiated when the shear crack, after propagating through this refined structure entered the structure formed due to heating just below the upper critical temperature. V-notch Charpy specimens with structures simulating those of these two zones, i.e. the refined structure and the intercritical structure, were prepared by heating to 1700 and 1500°F respectively and then still mineral oil quenching. In Figure 30 the synthetically produced structures are compared with the appropriate weld H.A.Z. structures. V-notch Charpy impact curves for these structures are presented in Figure 31 along with the previously presented curve for specimens quenched from 2200°F. The 10 ft.-lb. transition temperatures from these curves are presented in Table VI.

TABLE VI

Charpy 10 Ft.-Lb. Transition Temperatures for Synthetic H.A.Z. Structures of A-201 Steel

Structure	Heat Treatment Temperature °F	Transition Temp. °F
Coarse	2200	+5
Refined	1700	-105
Intercritical	1500	+40

These data are clearly in agreement with the previously observed fracture behavior of the specimens welded with E6010 electrodes and not postheated. The structure which in the Kinzel test produces a thin fibrous ring, thus throwing the lateral contraction above 1%, is definitely tougher than the structures on either side of it which fail by cleavage.

CONCLUSIONS - A-201 STEEL

1. Welding decreases the notch toughness of Kinzel specimens of the A-201 steel by providing a structure either in the coarse grains of the H.A.Z., in the weld metal, or at the fusion line which can initiate cleavage more readily than the base material itself. Any one or combinations of the above structures might be responsible for cleavage crack initiation.
2. The amount of decrease in notch toughness due to welding is limited first by the ability of a structure within the H.A.Z. and second by the ability of the base metal to prevent cleavage crack propagation at sufficiently high temperatures. The tough structure within the H.A.Z. consists of refined grains, which are produced when the base plate is heated to temperatures just above the upper critical temperature.
3. Postheating improves the notch toughness of welded specimens. At present the reasons for this improvement are obscure, although they are probably tied up with an improvement in the properties of the weld metal, fusion line or H.A.Z.

GENERAL DISCUSSION

Although only three steels have been included in this investigation, it is believed that the general conclusions concerning fracture behavior are applicable to other steels and that a general understanding of the effect of welding on Kinzel specimen behavior is now within reach. This understanding is best obtained through the realization of the importance of two of the basic concepts of brittle fracture: (1) Initiation of cleavage failure and (2) propagation of cleavage failure.

The ductility transition temperature of a steel as determined by unwelded Kinzel specimens is associated primarily with the ease or difficulty with which a cleavage crack can be initiated in that steel and not with the cleavage crack propagating properties of the steel. That this is true is apparent when two experimental observations are considered. First, in unwelded specimens when a cleavage crack is initiated at relatively low values of deflection, it always propagates throughout essentially the entire specimen; i.e. propagation of the crack is not prevented by the base material. As a matter of fact this is true even up to relatively high temperatures when the cleavage crack is initiated by structures other than that base material, e.g. the H.A.Z. due to welding. Second, in specimens which are tested at the ductility transition temperature (about 1% lateral contraction) there is almost a complete absence of a shear lip at the sides indicating that propagation is easy even where the complexity of the stress system is reduced. It is convenient to call the transition temperature at 1% lateral contraction for unwelded specimens T_i, i.e. the temperature at which initiation occurs relatively easily in the base material.

The welding of a Kinzel specimen usually introduces in that specimen a material or structure which can initiate cleavage failure more readily than the base material itself. If welding introduces a very effective crack initiator, then as the temperature of testing rises a temperature will be reached such that a cleavage crack once initiated will not be able to propagate easily through the base material. At this temperature, as has been observed, thin lines of fibrous appearance will be developed in the base material and the measured lateral contraction will rise abruptly, usually close to 1%. As testing temperature rises further the cleavage crack will encounter increasing resistance to propagation, the amount of base metal shear will increase, and the lateral contraction will rise further, usually above 1%. It is convenient to call the temperature above which a cleavage crack cannot propagate easily in the base material T_p. This temperature is a property of the base material as determined by the Kinzel test under constant testing conditions. Changing any of the test conditions such as rate of loading, notch geometry, etc., may change the position of T_p on the temperature scale.

In the Kinzel test T_p is very nearly the highest possible temperature to which the 1% lateral contraction transition temperature can rise as a result of welding. If welding produces a structure which can initiate cleavage failure above T_p, then the lateral contraction will rise to or above 1% at T_p or slightly above T_p. For any one steel, therefore, the welded transition temperature must be between T_1 and T_p approximately, both temperatures being properties of the base material itself.

The value that the welded transition temperature takes between T_1 and T_p depends primarily upon the notch toughness of the H.A.Z. and weld metal with respect to the highest temperature at which either of them can initiate cleavage failure in the Kinzel test. The notch toughness of the weld metal and the various H.A.Z. regions depends ultimately, of course, upon the welding conditions, the electrode type and composition, and the composition and response to welding of the base material. Thus the weld zone controls the transition temperature by determining the temperature t_1 between T_1 and T_p at which brittle failure can be initiated. If t_1 is greater than T_p, then T_p will determine the transition temperature.

The weld zone may influence the transition temperature in an additional way. If, due to the heat of welding, a structure is produced in the heat affected zone which at sufficiently high temperatures can prevent easy propagation of a cleavage crack initiated above it, then shearing within this region may raise the lateral contraction above 1%. If the lowest temperature at which this can occur is t_p, then in order for this mechanism to determine the Kinzel test transition temperatures t_p must be less than T_p and T_i.

The foregoing discussion may be summarized and perhaps clarified with the aid of the schematic diagrams in Figure 32. In these diagrams the symbols are defined as follows:

T_i - Temperature at which cleavage is <u>initiated</u> easily in unwelded specimens. Defined here at 1% lateral contraction.

T_p - Lowest temperature at which the <u>base</u> material can prevent easy <u>propagation</u> of a cleavage crack and thus raise the lateral contraction to 1%.

t_i - Highest temperature at which any area in the <u>weld zone</u> can <u>initiate</u> cleavage failure.

t_p - Lowest temperature at which any area in the <u>weld zone</u> can prevent easy <u>propagation</u> of a cleavage crack initiated above it and thus raise lateral contraction to 1%.

In Figure 32 the horizontal axis represents the temperature scale while the vertical axis has no meaning. The arrow indicates where the 1% lateral contraction transition temperature is located. Figure 32a represents the situation for unwelded Kinzel specimens of any one steel. Here the transition temperature is determined by T_i. Since T_i and T_p are properties of the base material, their position on the temperature scale will remain constent for welded specimens. Figure 32b represents the situation when the above steel is welded under a particular set of welding conditions. The transition temperature here is determined by t_i. If the welding conditions are made more severe so that t_i rises above T_p, then, as Figure 32c shows, the transition temperature is determined by T_p. An additional increase in t_i due to still more severe welding conditions will not affect the transition temperature. Figure 32d shows how postheating reduces t_i, thus lowering the transition temperature. Here the assumption is made that postheating does not change T_i or T_p appreciably. This is, of course, not true for all steels, since postheating has been found to improve the toughness of some steels and to embrittle others. In Figure 32e welding conditions are such that a tough area within the H.A.Z. has been produced which at temperatures higher than t_p prevents crack propagation. The transition temperature is thus determined by t_p.

There are, of course, additional variations of the diagrams in Figure 32. The important thing, however, is the fact that three factors must be considered in attempting to understand how welding influences the Kinzel test transition temperature. These three factors are:

1. The role of the weld zone in initiating cleavage failure.

2. The role of the weld zone in preventing propagation of cleavage failure.

3. The role of the base material in preventing propagation of cleavage failure.

Most surprising is the revelation that under some conditions the properties of the base material itself may be all important in determining the welded transition temperature. This fact is important since it may explain among other things the beneficial effect of prenormalizing on welded transition temperature. Perhaps prenormalizing is beneficial almost entirely because it imparts increased notch toughness to the base plate material. The influence of the base material may also have to be considered when attempting to study the effect of other variables on weldability. For example, the beneficial effects of preheating may not be evident if the welded transition temperature is being controlled by the base material instead of the H.A.Z.

The author realizes, of course, that the general applicability of the concepts proposed in this discussion to a wide variety of steels and welding conditions is not certain. Their confirmation or modification will depend upon further experimentation. Additional research should include:

1. The investigation of fracture behavior of a wide variety of steels.

2. The investigation of the relationship, if any, between T_p and V-notch Charpy transition curves of base material.

3. The investigation of the effect of variation in welding conditions, particularly heat input, on transition temperature and fracture behavior with special attention to the influence of T_p.

4. Further investigation of the properties of weld zone structures including both the H.A.Z. and weld metal.

GENERAL CONCLUSIONS

1. Welding decreases the notch toughness of Kinzel specimens by providing a structure either in the weld metal or in the heat-affected-zone which can initiate cleavage failure more readily than can the base material itself.
2. The amount of decrease in notch toughness due to welding may be limited by a tough structure within the H.A.Z. which at sufficiently high temperature will prevent propagation of a cleavage crack. Shear failure within this tough region may raise the lateral contraction close to or above 1%.
3. An absolute limitation on the rise in Kinzel test transition temperature due to welding exists because of the properties of the base material itself. Thus the transition temperature cannot rise much above the temperature at which a cleavage crack cannot propagate easily in the base material.

4. Postheating improves the notch toughness of welded specimens by increasing the notch toughness of the structures responsible for cleavage crack initiation thus reducing the temperature at which they become effective.

5. The improvement in notch toughness due to postheating may be limited by the degree of improvement that the weld metal undergoes when postheated. Thus, although the notch toughness of critical areas of the H.A.Z. are substantially improved by postheating, there may be only a slight improvement in the notch toughness of the weld metal. At sufficiently low temperatures the weld metal may initiate a cleavage crack which can propagate through a relatively tough H.A.Z.

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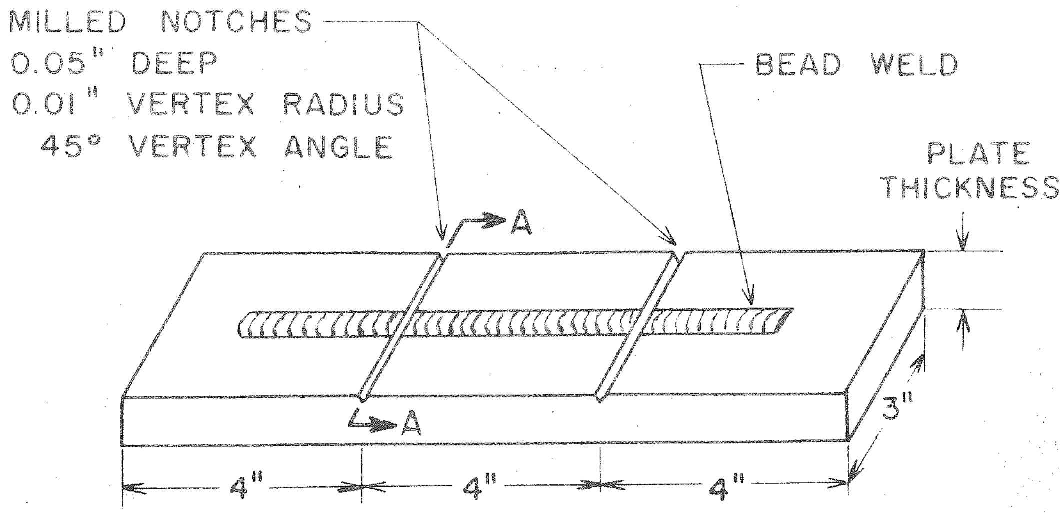


Figure 1. Details of Kinzel Type Longitudinal-Bead-Weld Notch-Bend Specimen.

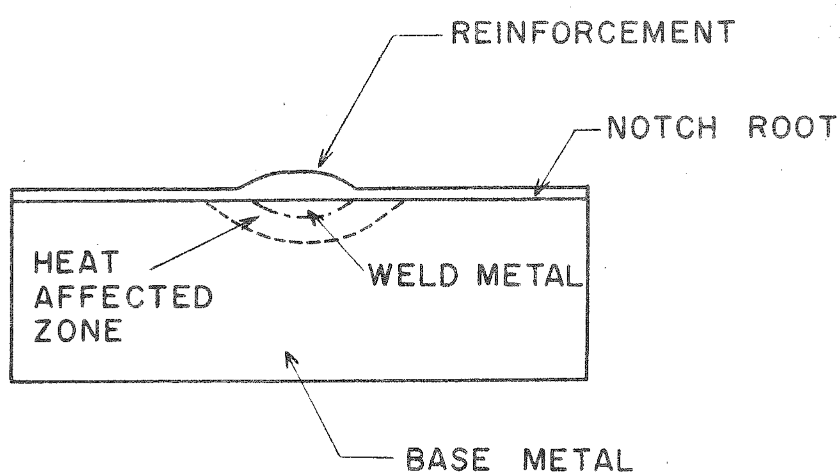


Figure 2. Section of Figure 1 at AA Showing Areas Exposed at Notch Root of Welded Kinzel Specimen.

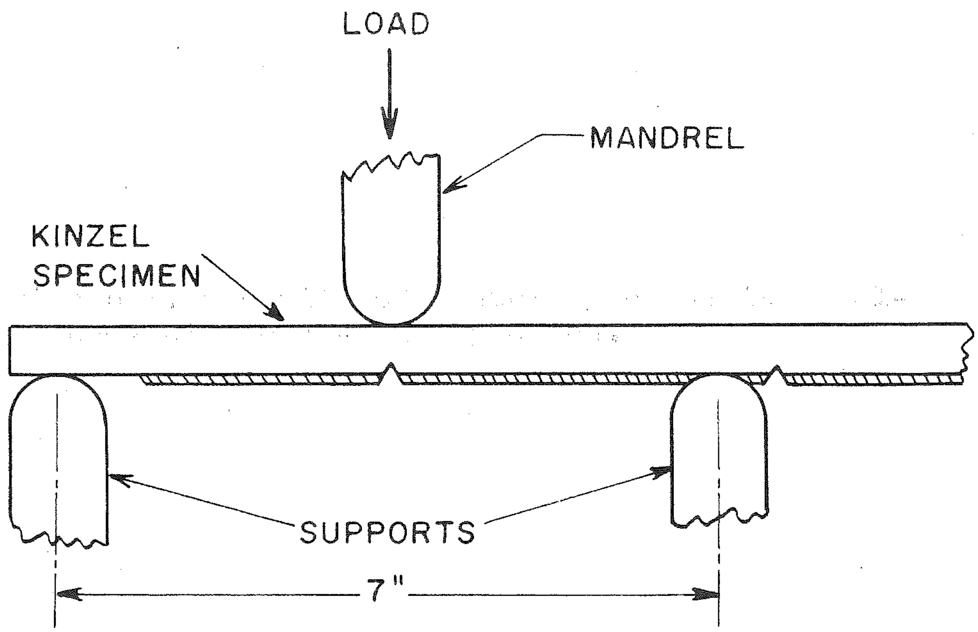


Figure 3. Slow Bend Test of Kinzel Specimen.

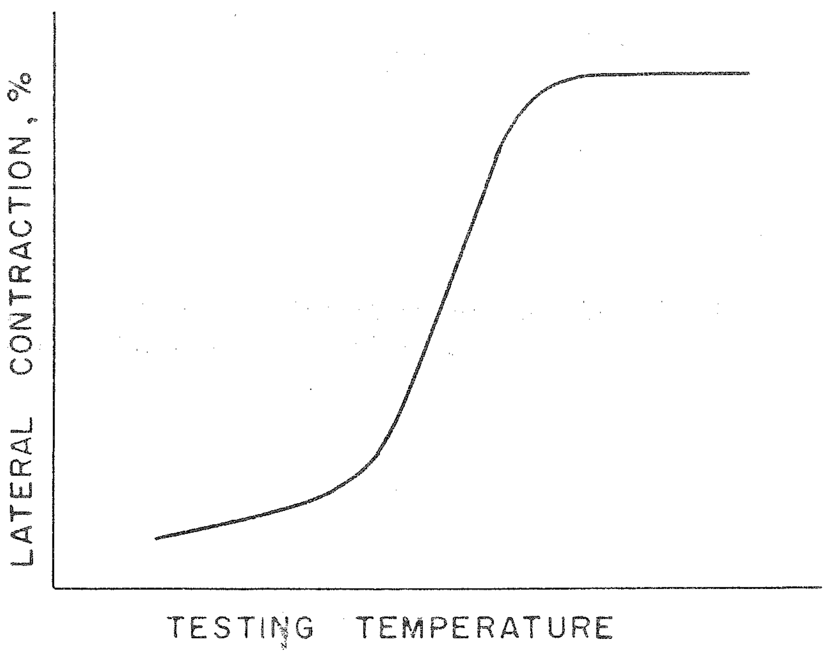
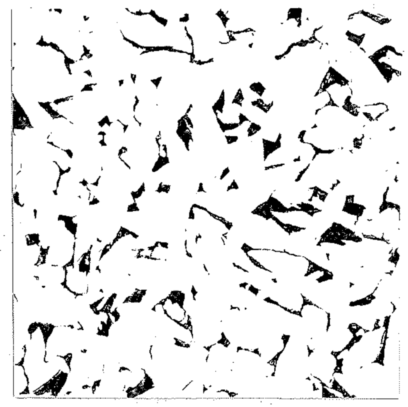


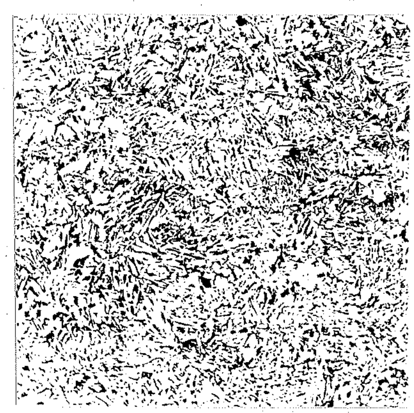
Figure 4. Transition Behavior of Kinzel Specimens as Determined by Lateral Contraction.

A-7



A-201

1" A-302



½" A-302

Figure 5. Photomicrographs of Steels in As Received Condition.
100X Picral Etch

Figure 6. Photograph of Typical Kinzel Specimen Fracture Surface.

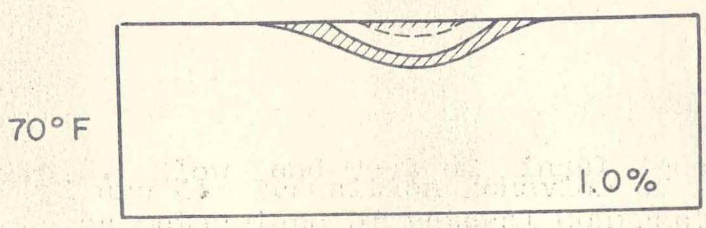


Figure 7. Drawing Illustrating Fracture Pattern of Figure 5.

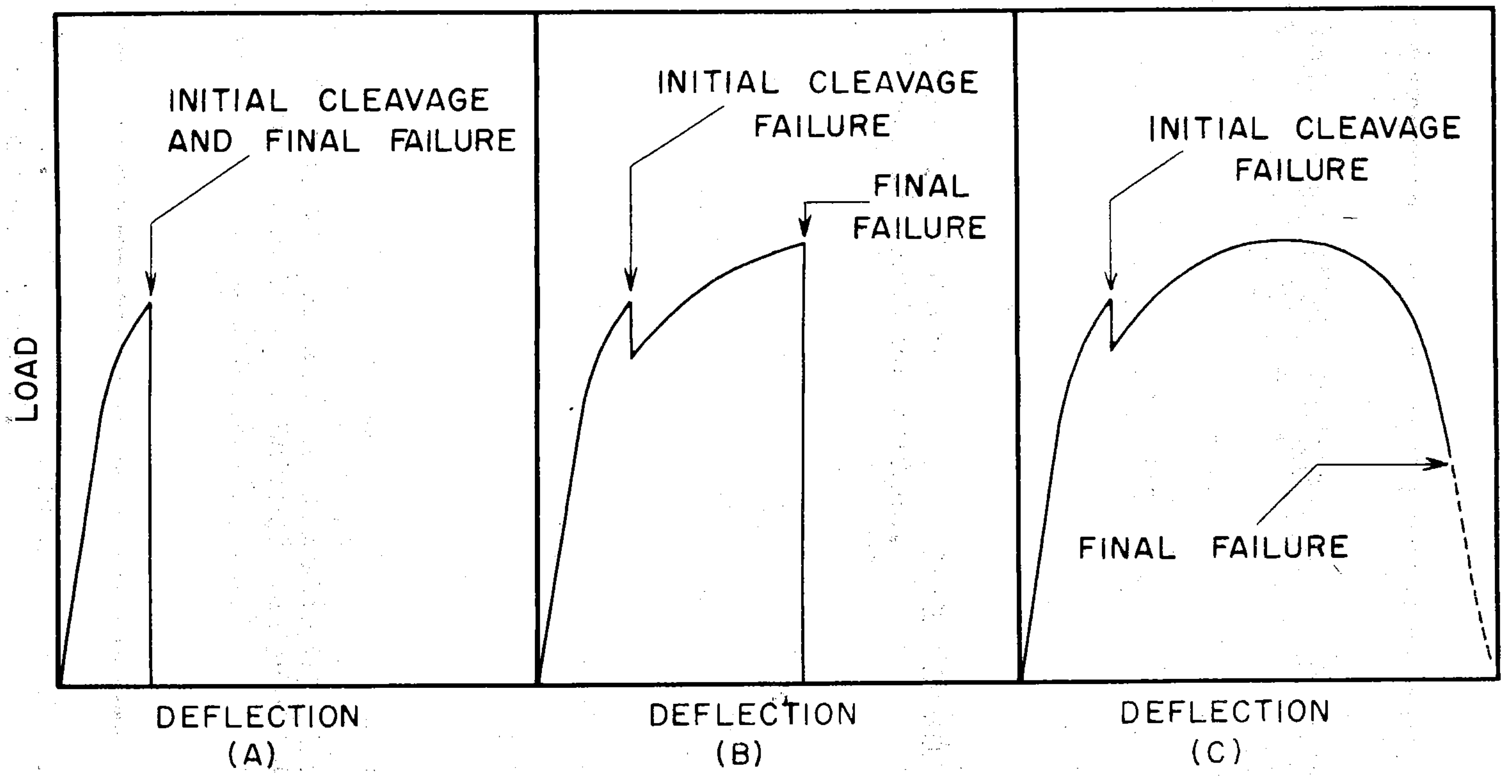


Figure 8. Load Deflection Curves of Typical Kinzel Specimens, Showing How Deflection at Initial Cleavage Failure and at Final Failure Are Obtained.

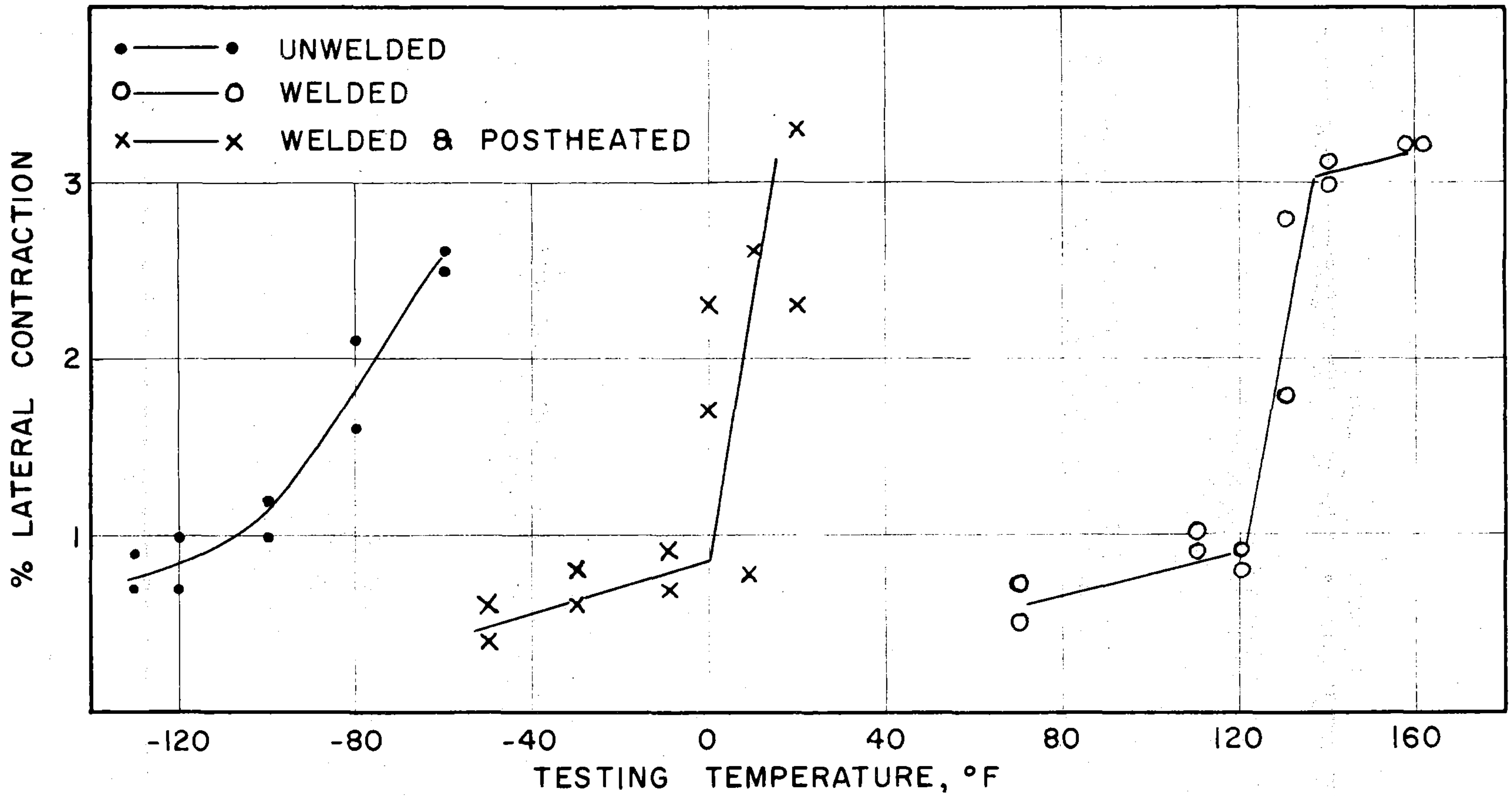


Figure 9. Kinzel Test Transition Curves for 1" A-302 Steel.

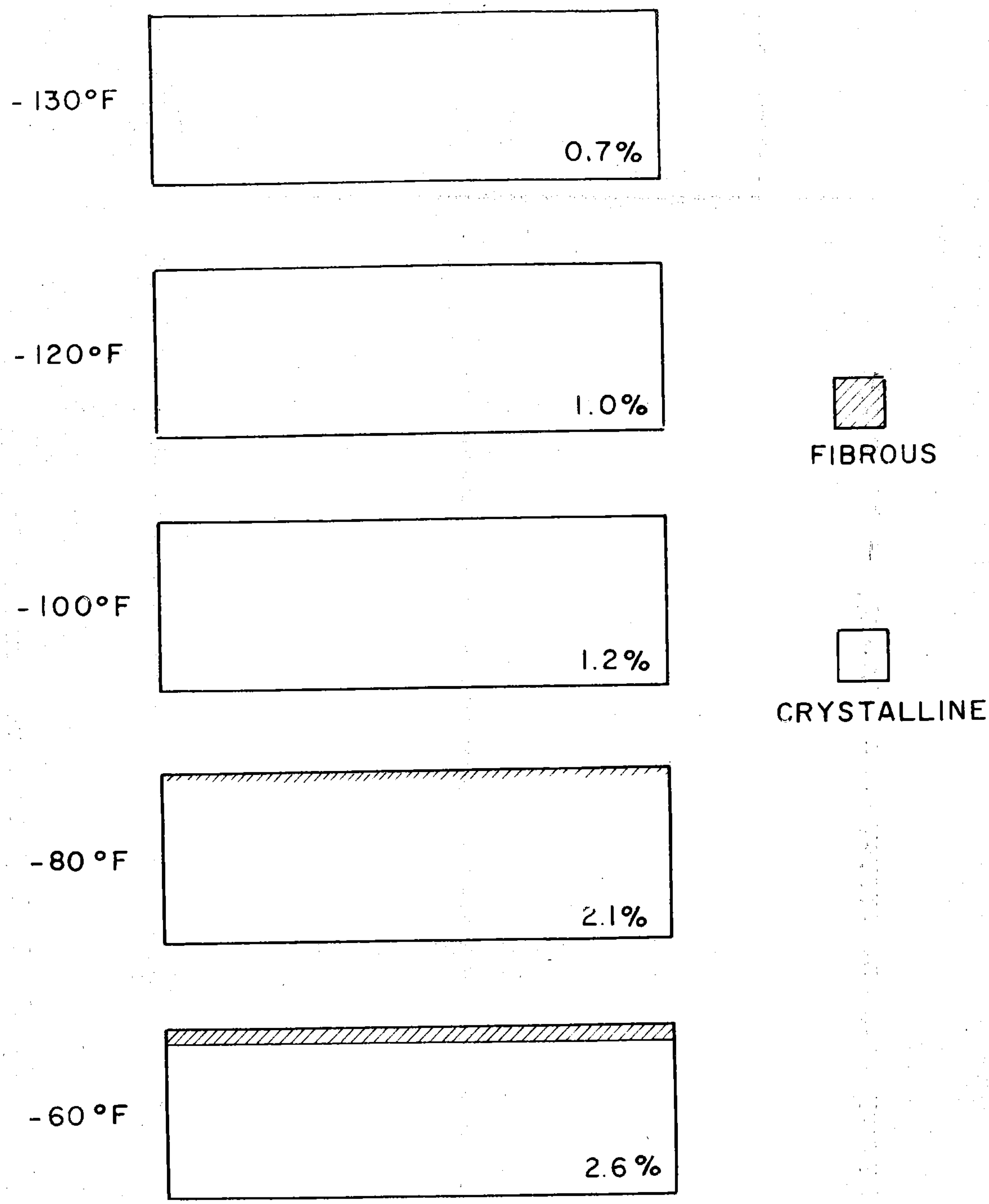


Figure 10. Fracture Behavior of Kinzel Specimens of 1" A-302 Steel, Unwelded.

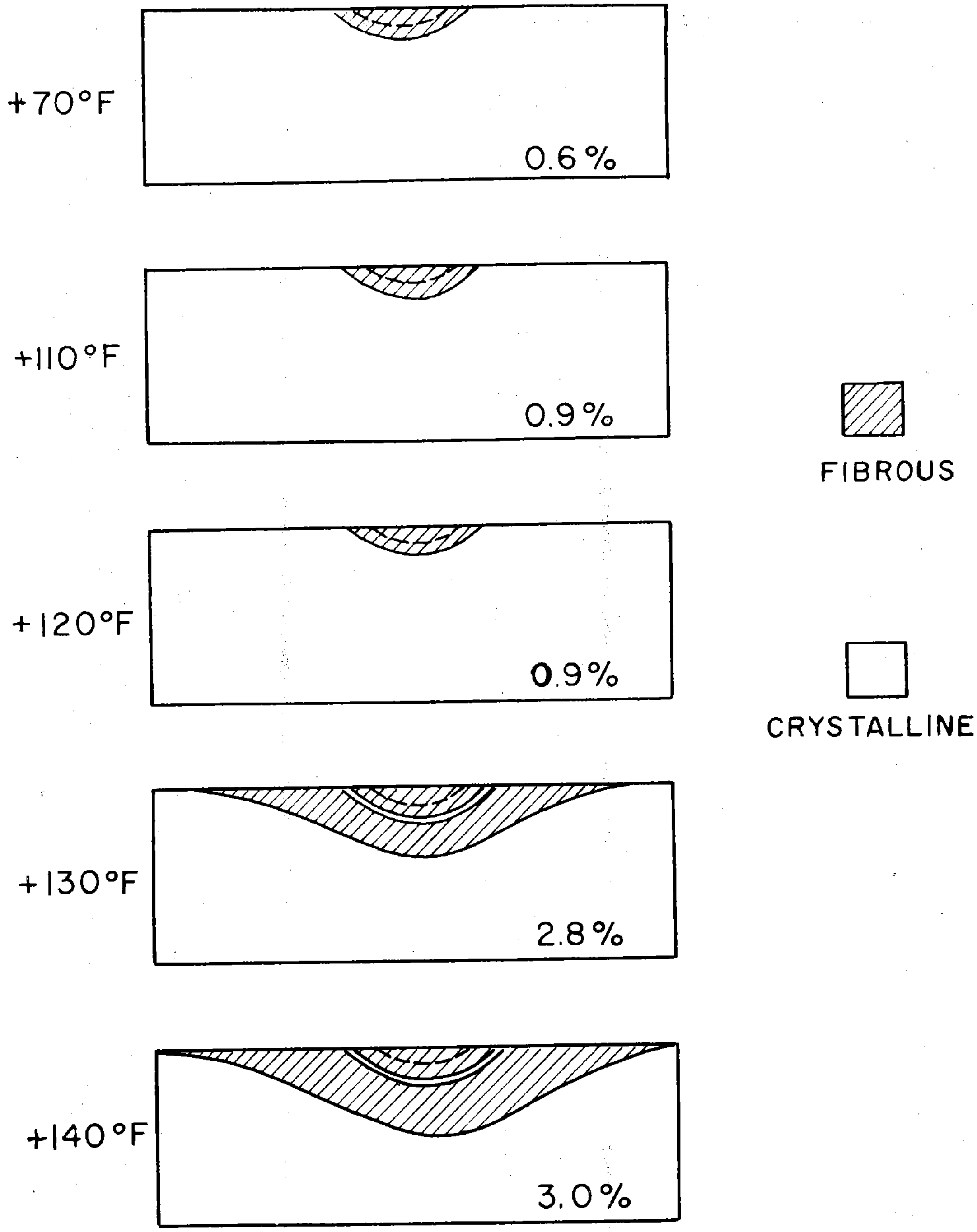


Figure 11. Fracture Behavior of Kinzel Specimens of 1" A-302 Steel, Welded.

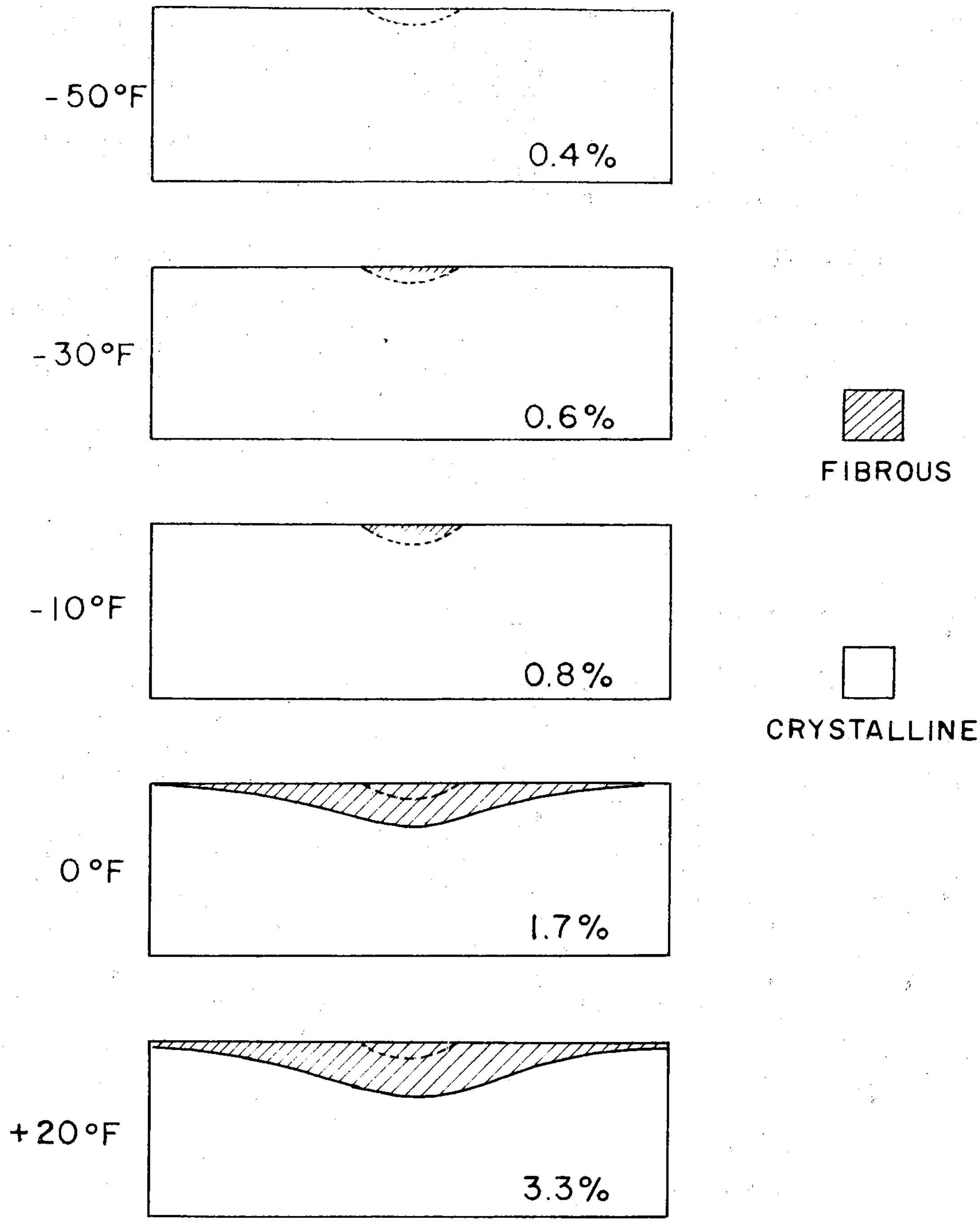


Figure 12. Fracture Behavior of Kinzel Specimens of 1" A-302 Steel, Welded and Postheated.

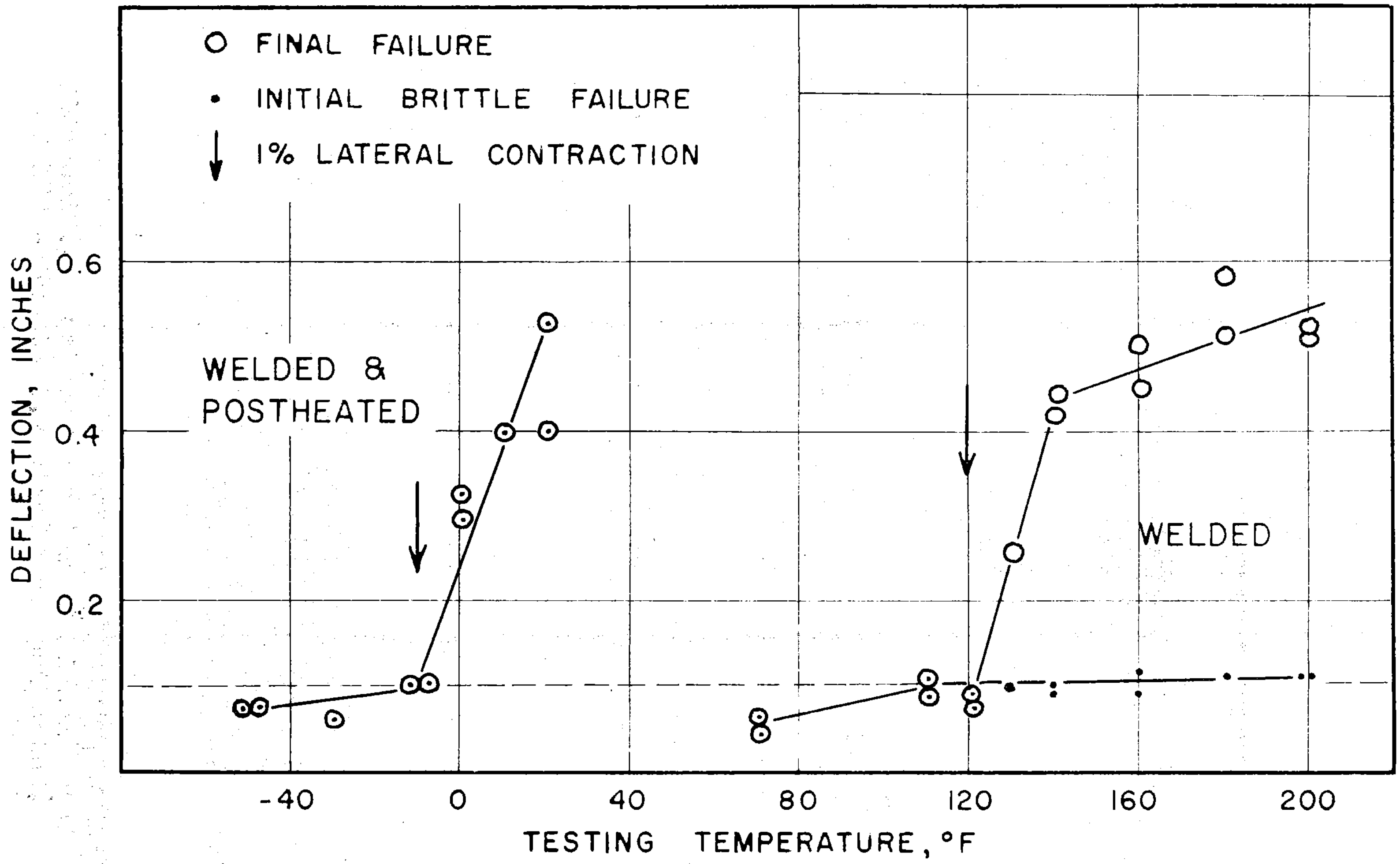


Figure 13. Transition Behavior of Kinzel Specimens of 1" A-302 Steel as Shown by Deflection.

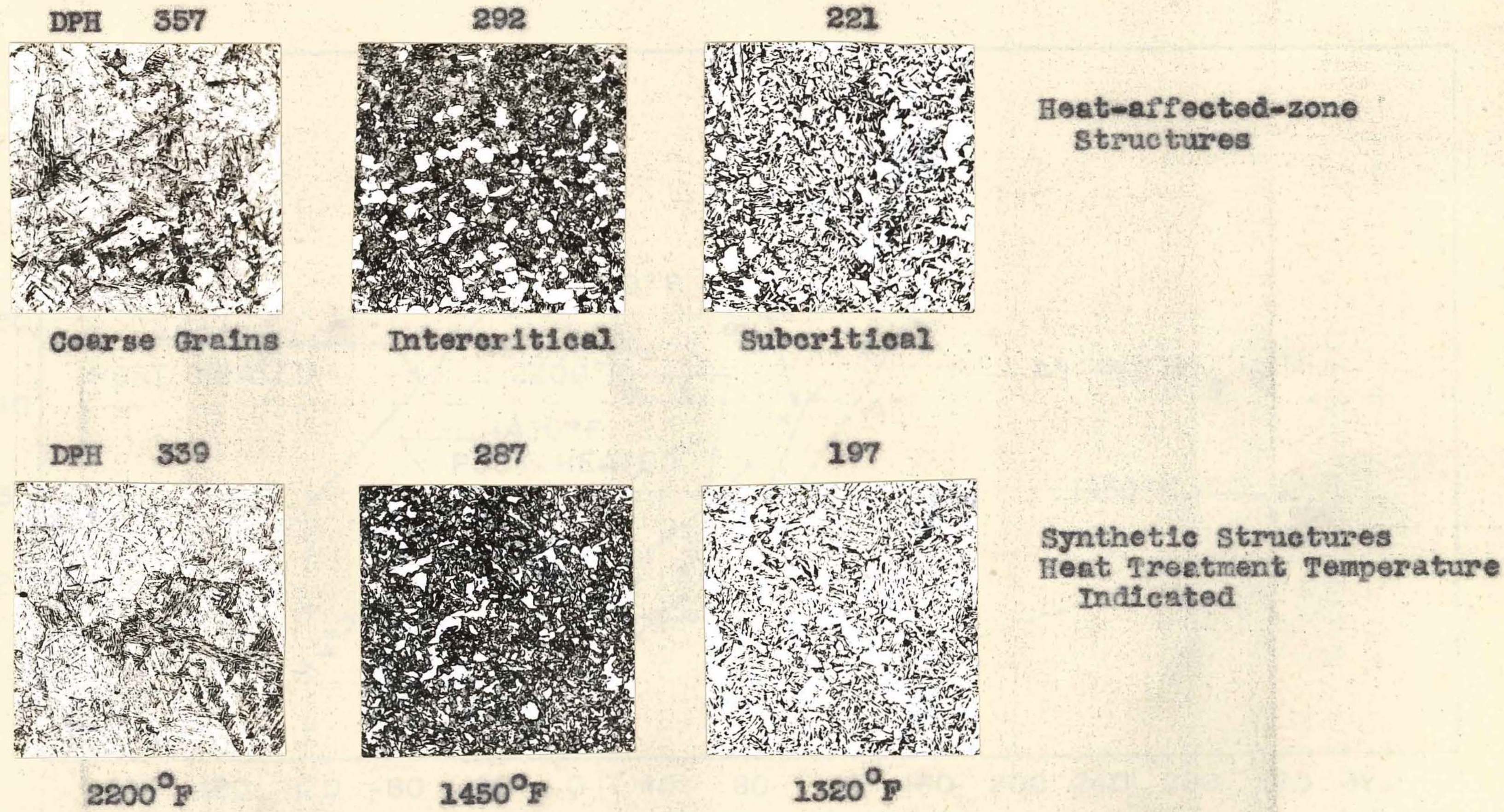


Figure 14. Comparison of Synthetic Structures with Actual Structures from the H.A.Z. of A-302 Steel. Picral Etch X100. 10 Kg Diamond Pyramid Hardness also Shown.

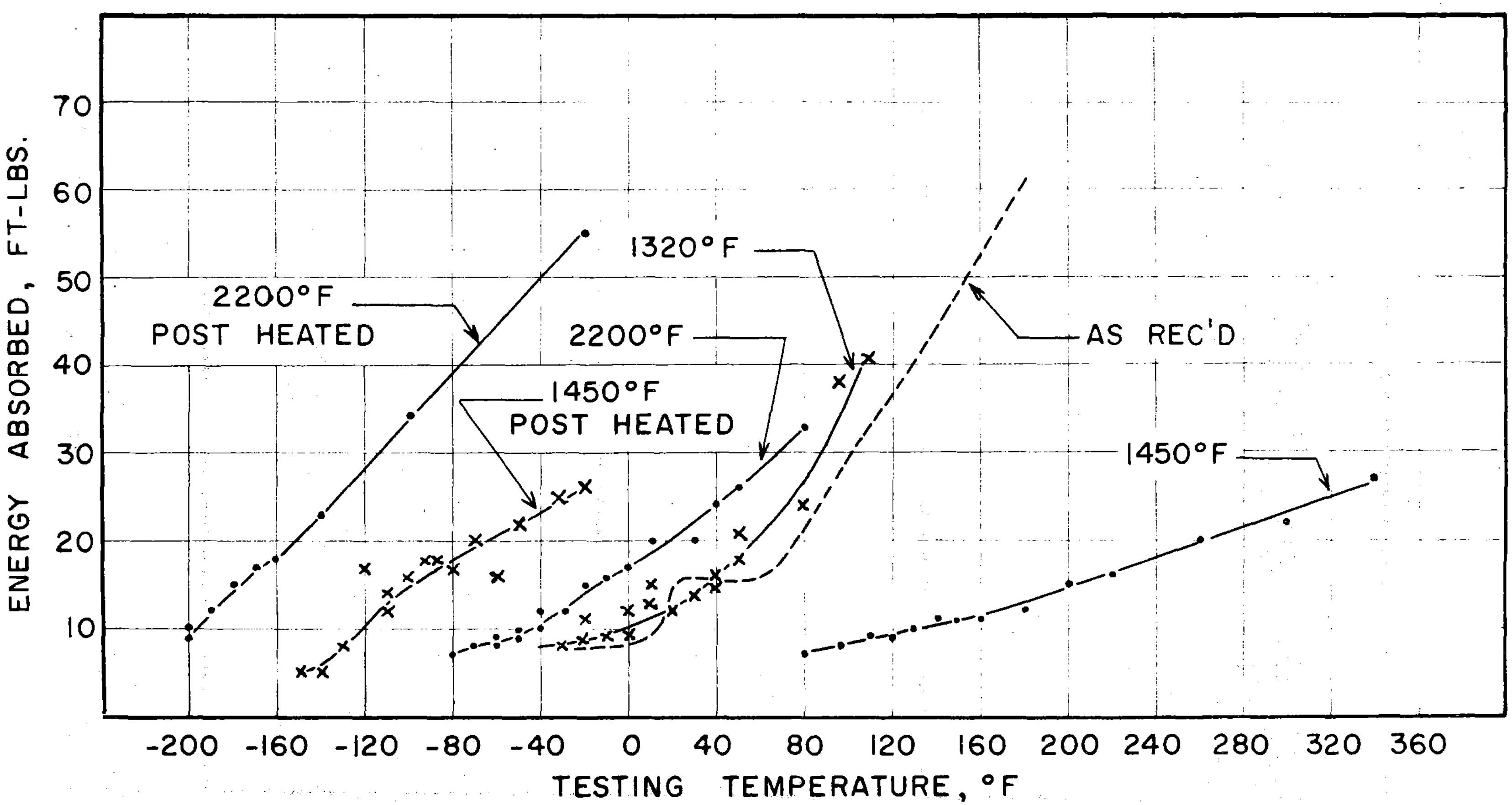


Figure 15. V-Notch Charpy Transition Curves for Synthetic H.A.Z. Structures of A-302 Steel.

1 inch

$\frac{1}{2}$ inch

Figure 16. Microstructures of Coarse Grains of H.A.Z. of 1 and $\frac{1}{2}$ inch thick A-302 Kinzel Specimens Welded at 6 inches/minute. X1000 Picral Etch

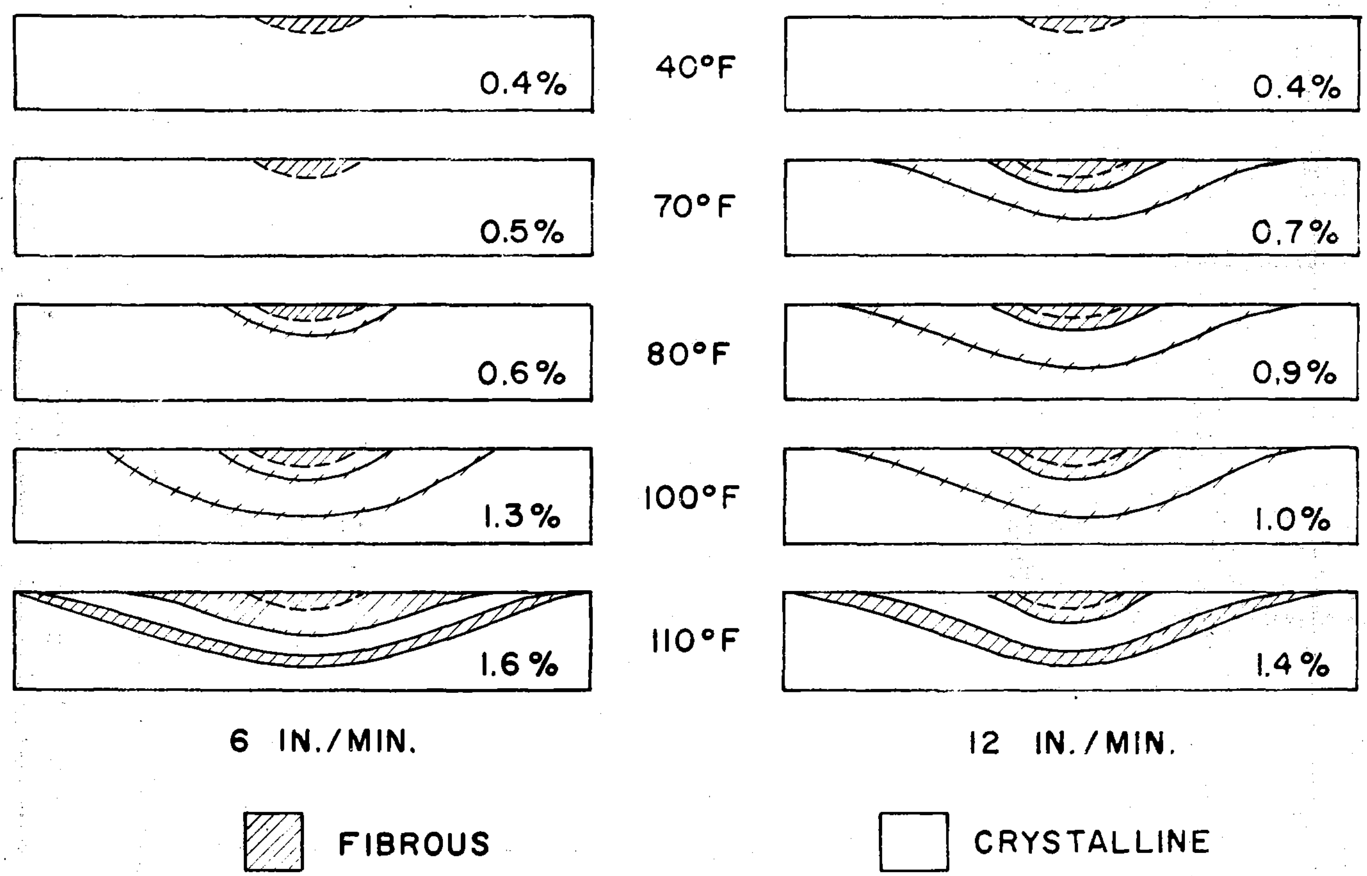


Figure 17. Fracture Behavior of 1/2 inch A-302 Steel Welded at 6 and 12 in./min.

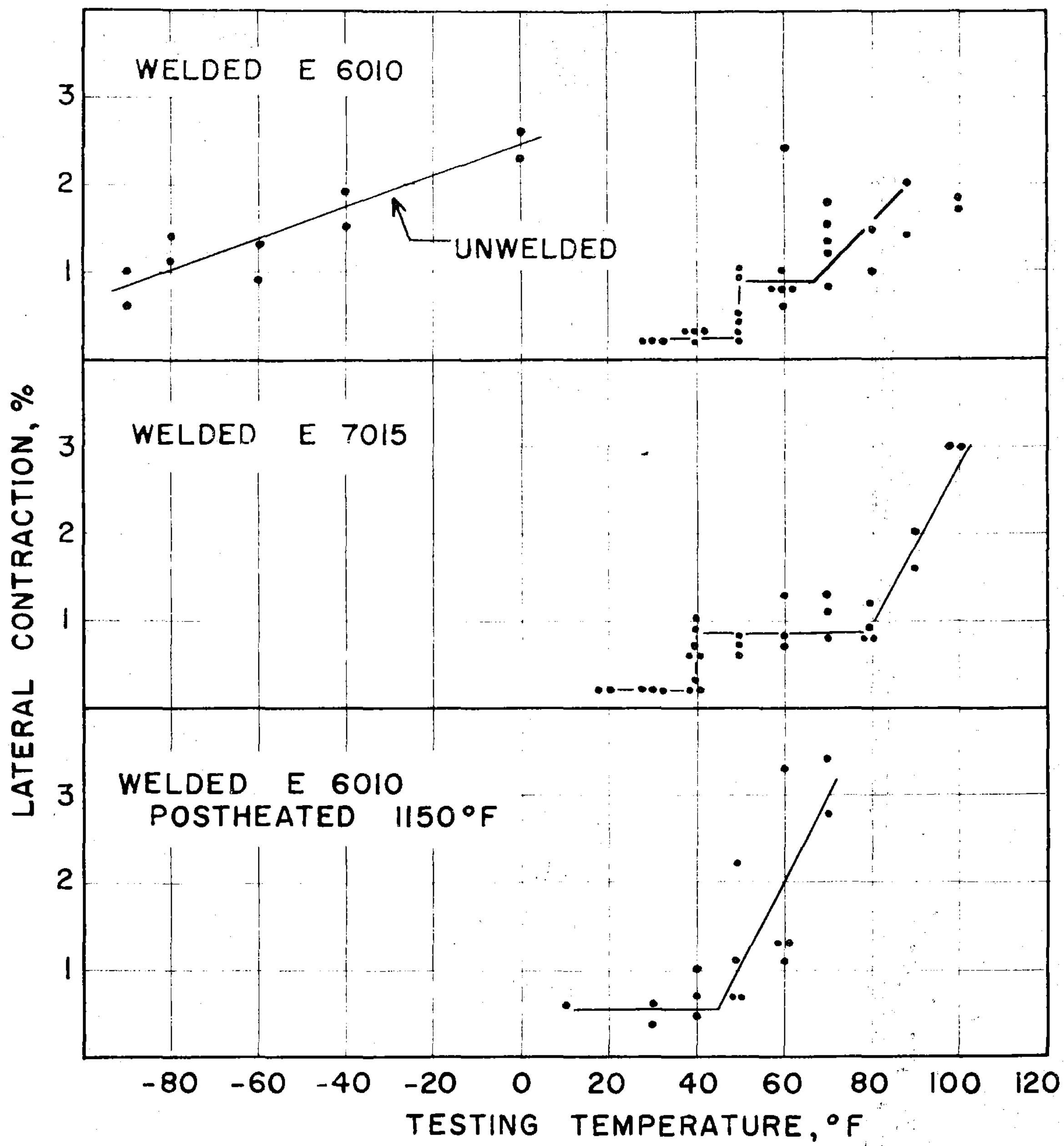


Figure 18. Kinzel Test Transition Curves for A-7 Steel.

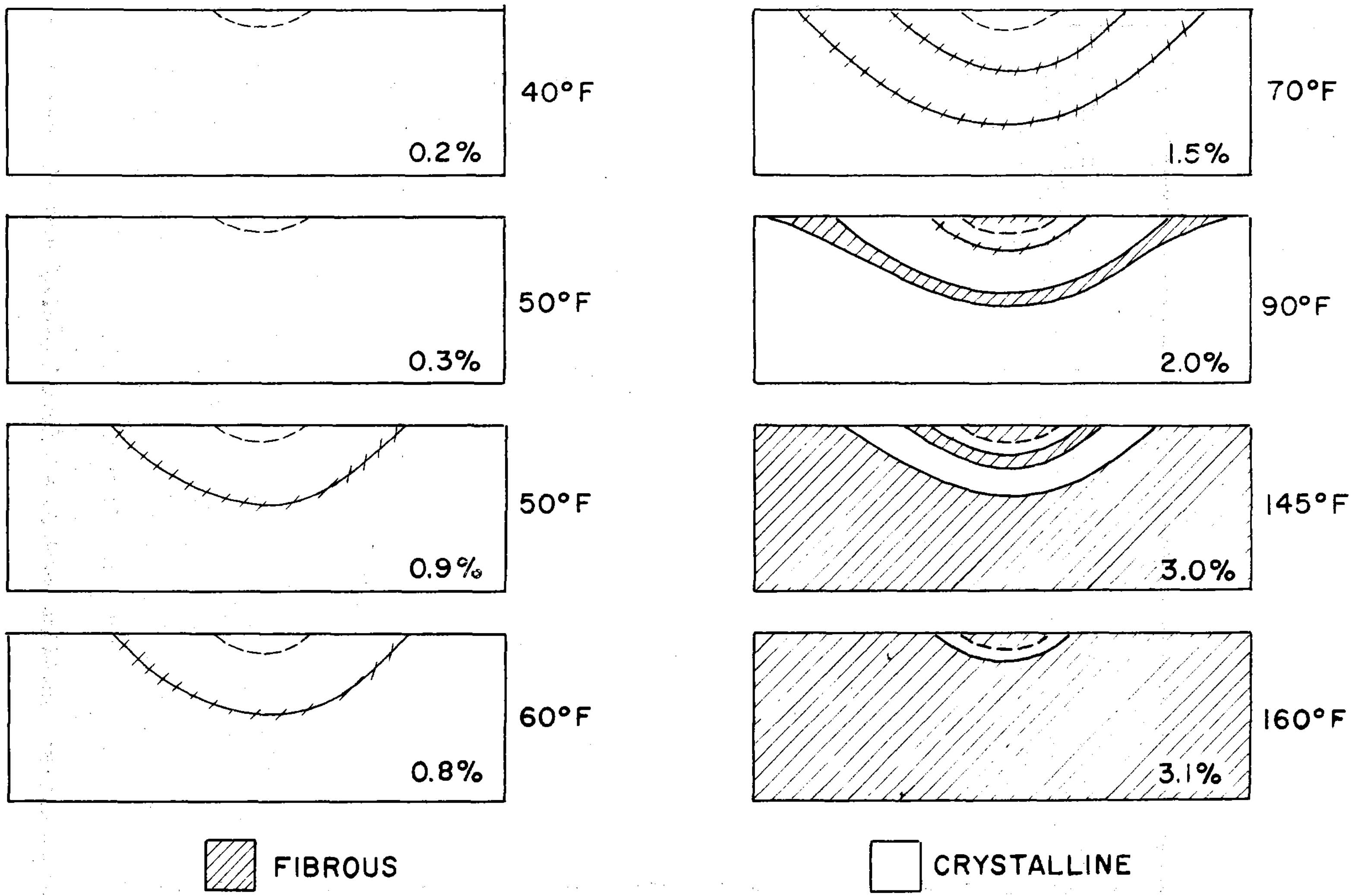


Figure 19. Fracture Behavior of Kinzel Specimens of A-7 Steel Welded with E6010 Electrodes.

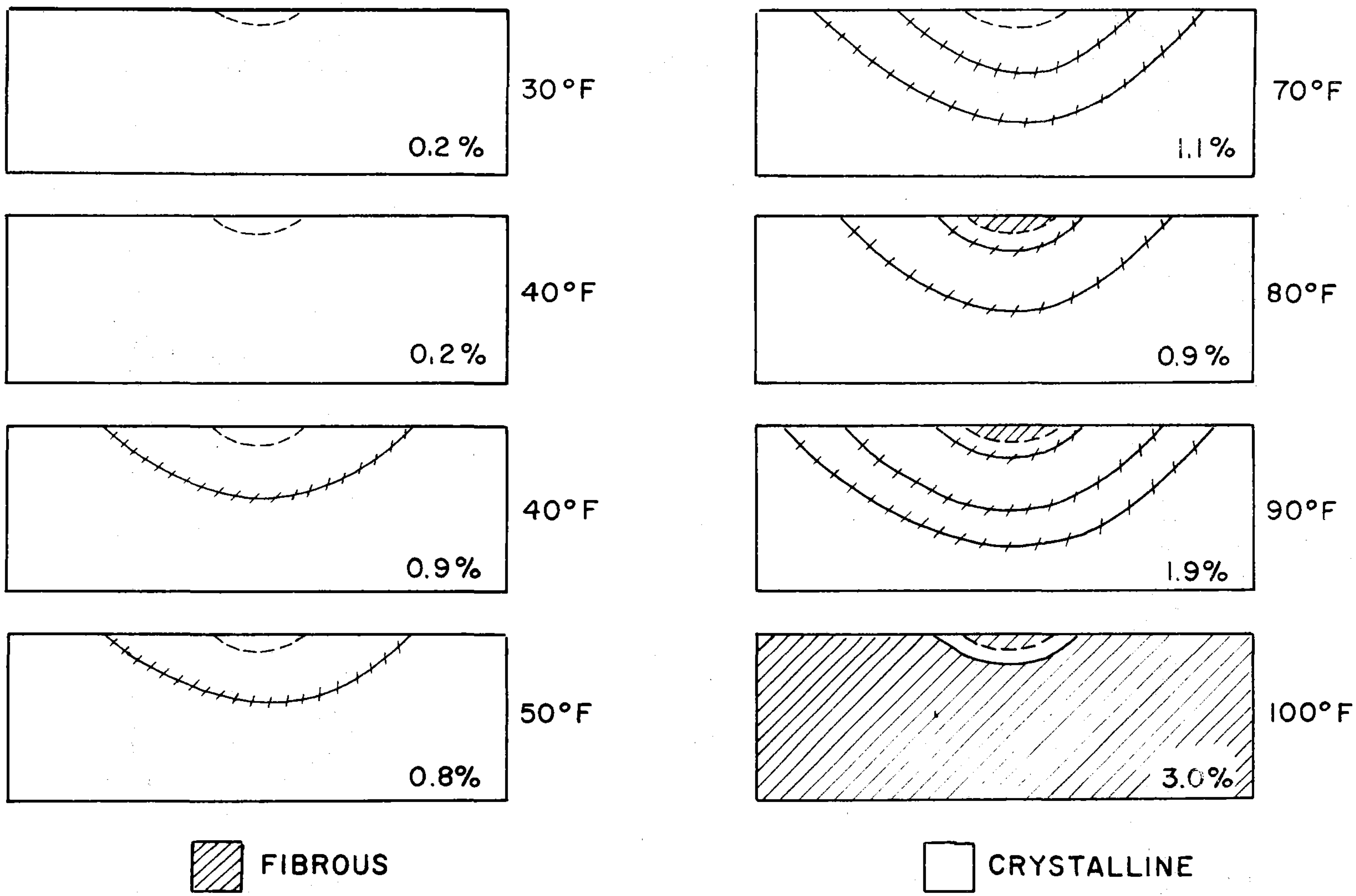


Figure 20. Fracture Behavior of Kinzel Specimens of A-7 Steel Welded with E7015 Electrodes.

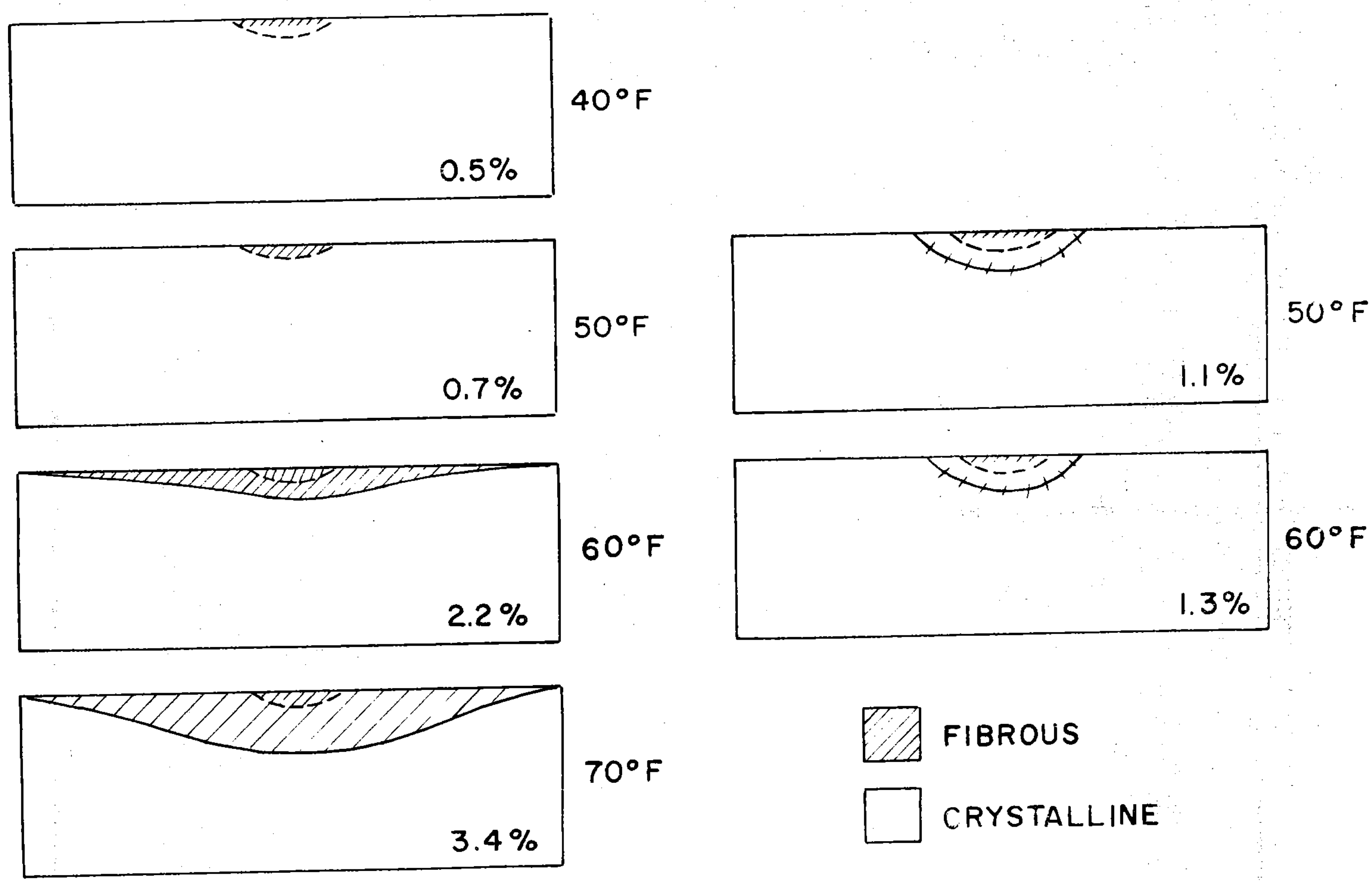


Figure 21. Fracture Behavior of Kinzel Specimens of A-7 Steel Welded with E6010 Electrodes and Postheated.

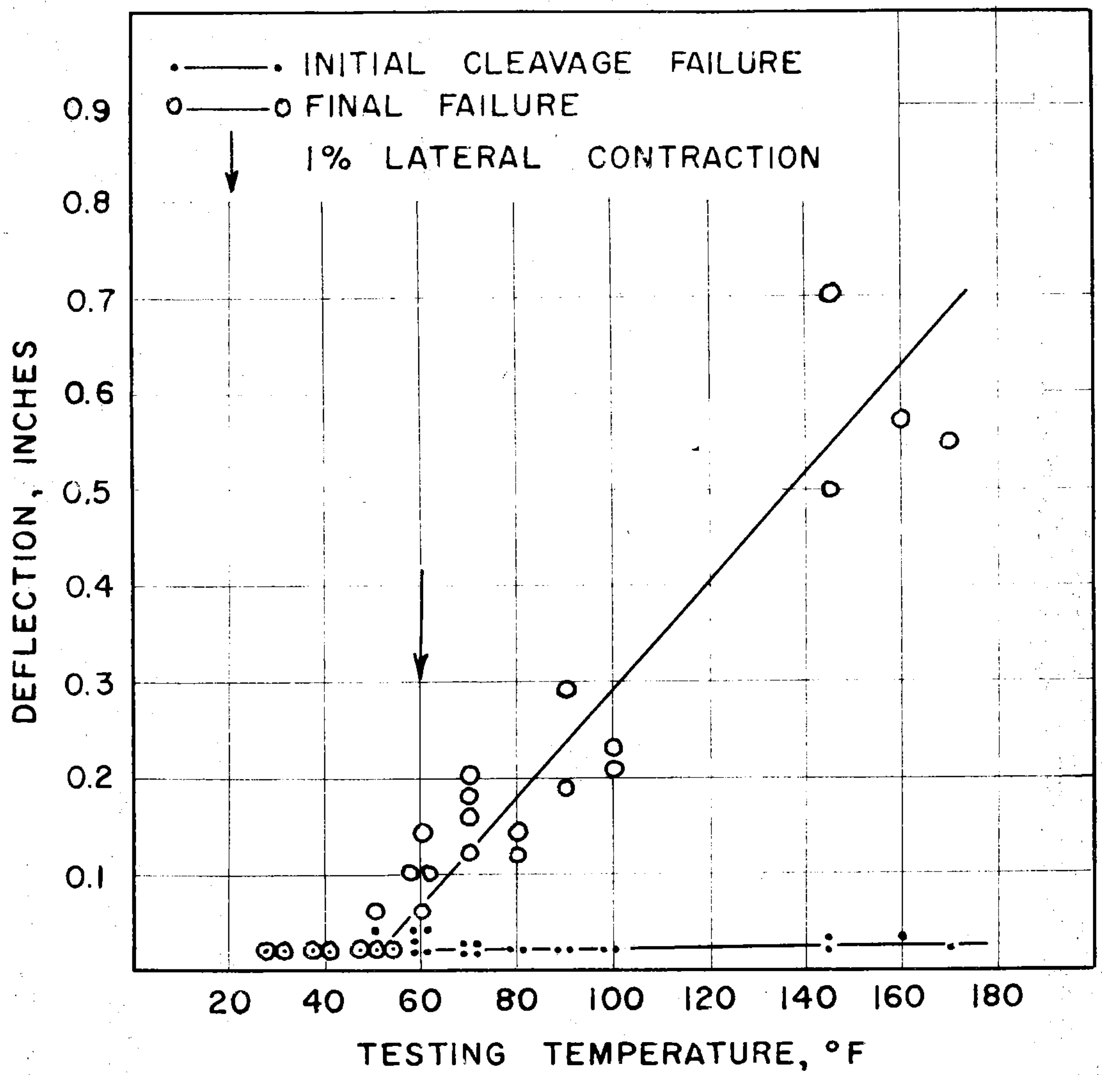


Figure 22. Transition Behavior as Shown by Deflection, A-7 Steel Welded with E6010 Electrodes.

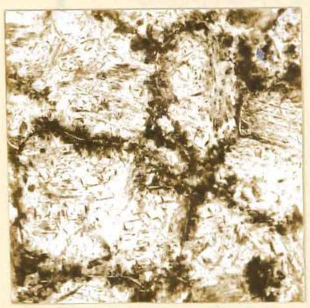
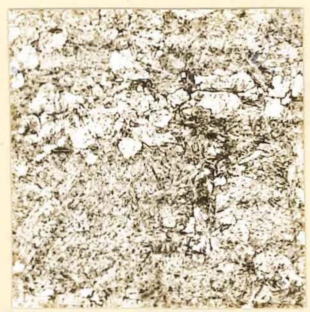
DPH 333	209	
		Structure of Coarse Grains of H.A.Z.
As Welded	Welded and Postheated	
DPH 327	212	
		Structures Produced Synthetically to Match Above Structures Heat Treated at 2200°F
As Quenched	Quenched and Postheated	

Figure 23. Comparison of Synthetic Structures with Actual Structures from the H.A.Z. of A-7 Steel. Picral Etch 100X. 10 Kg Diamond Pyramid Hardness also Shown.

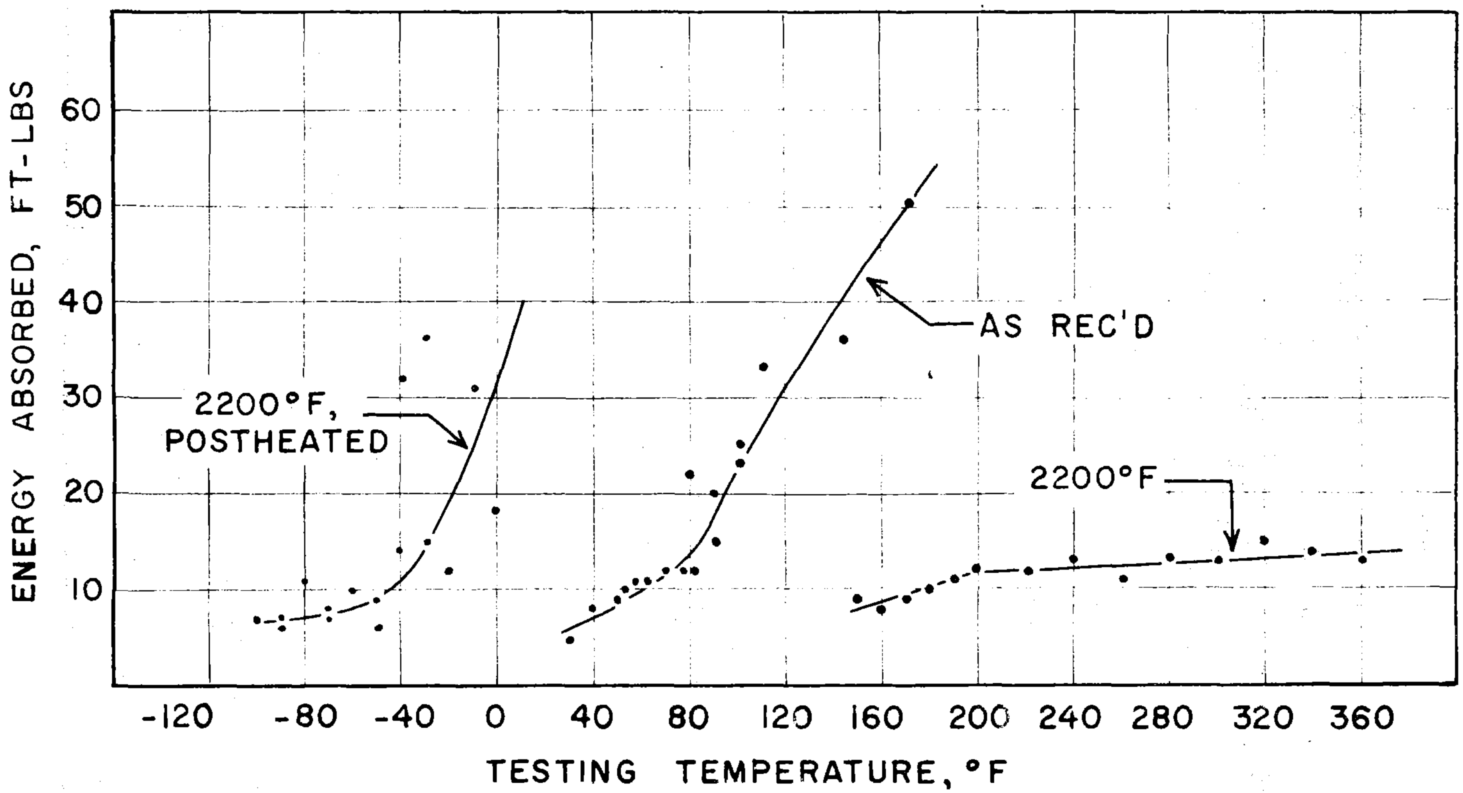


Figure 24. V-Notch Charpy Transition Curves for Synthetic H.A.Z. Structures of A-7 Steel.

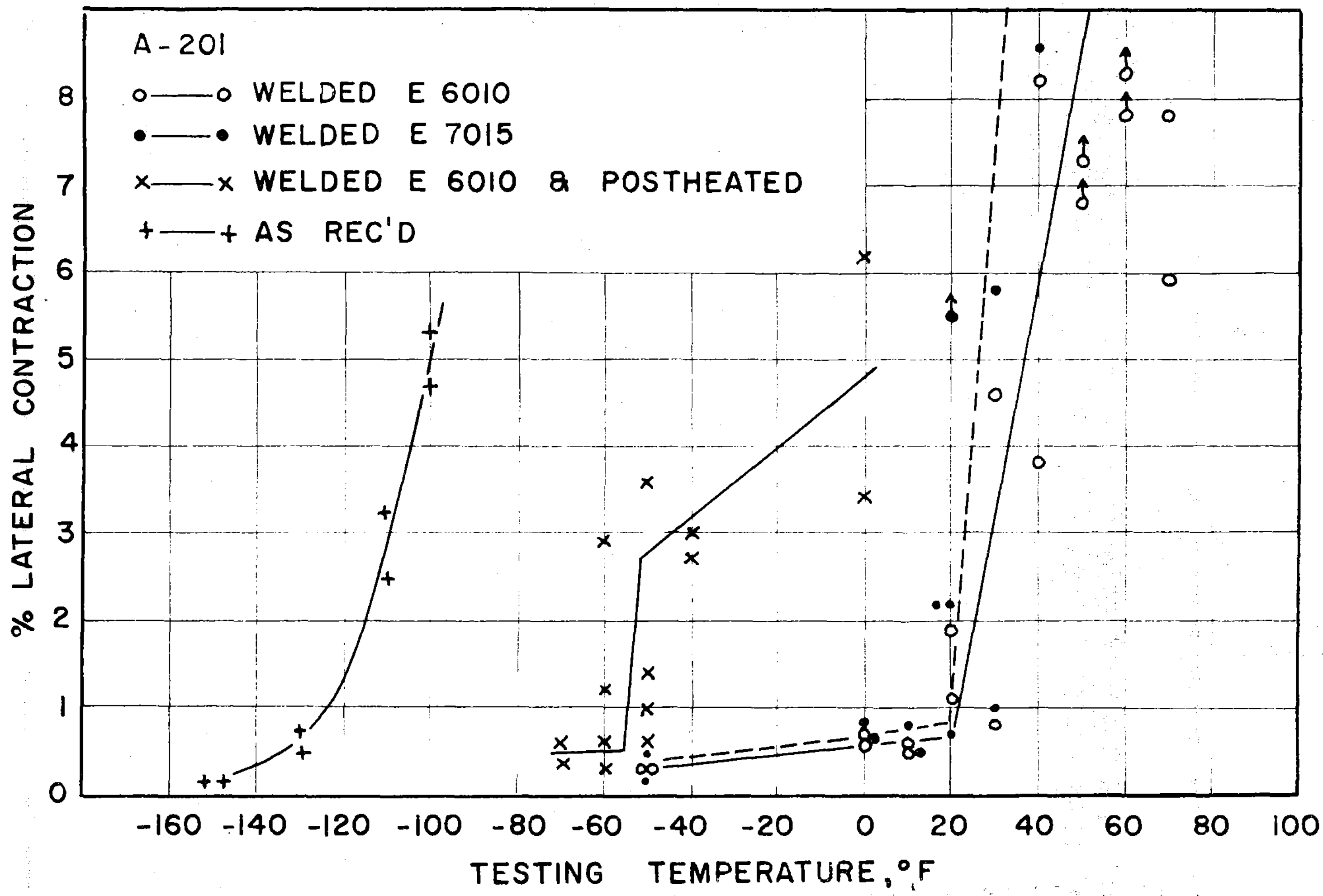


Figure 25. Kinzel Test Transition Curves for A-201 Steel.

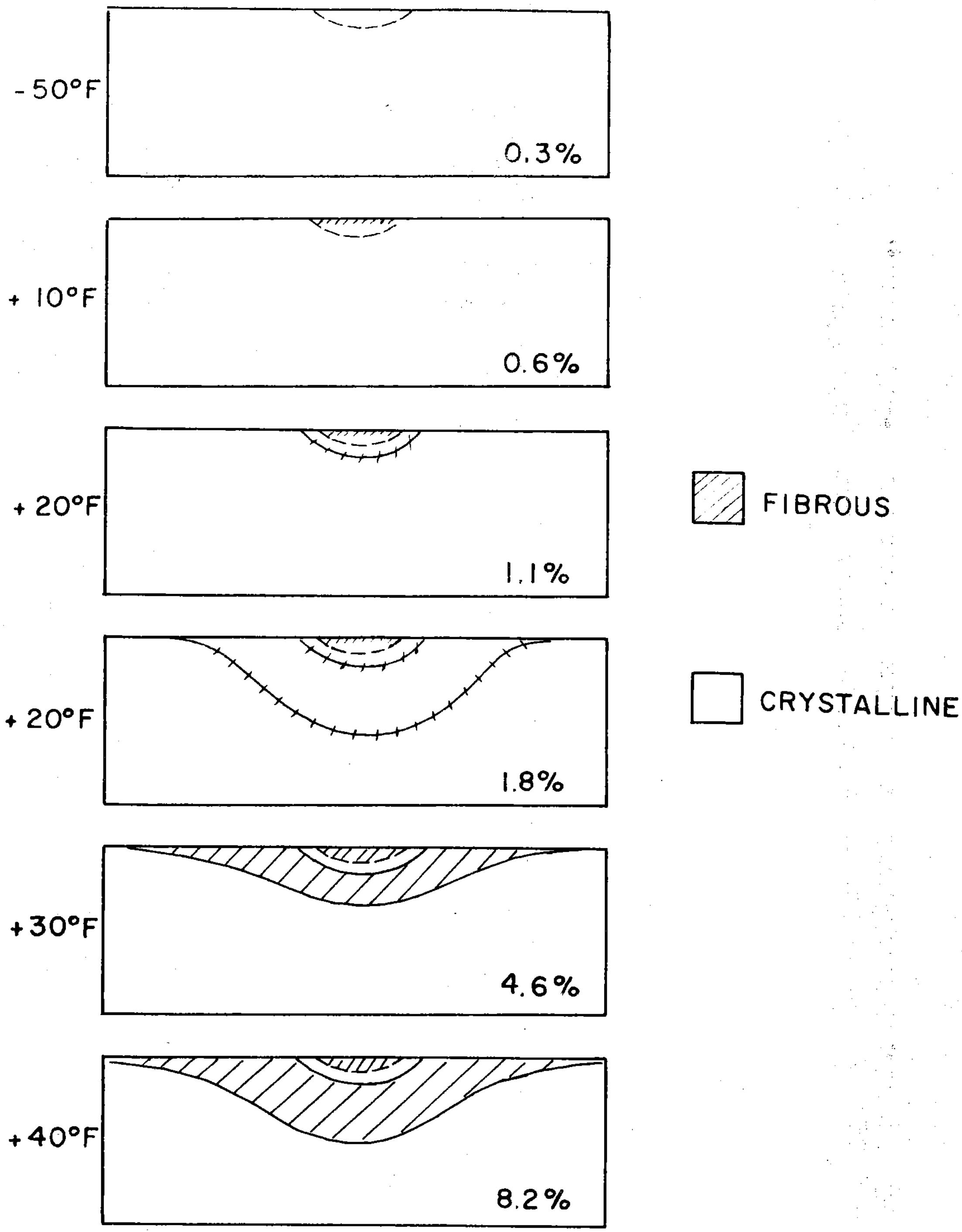


Figure 26. Fracture Behavior of Kinzel Specimens of A-201 Steel Welded with E6010 Electrodes.

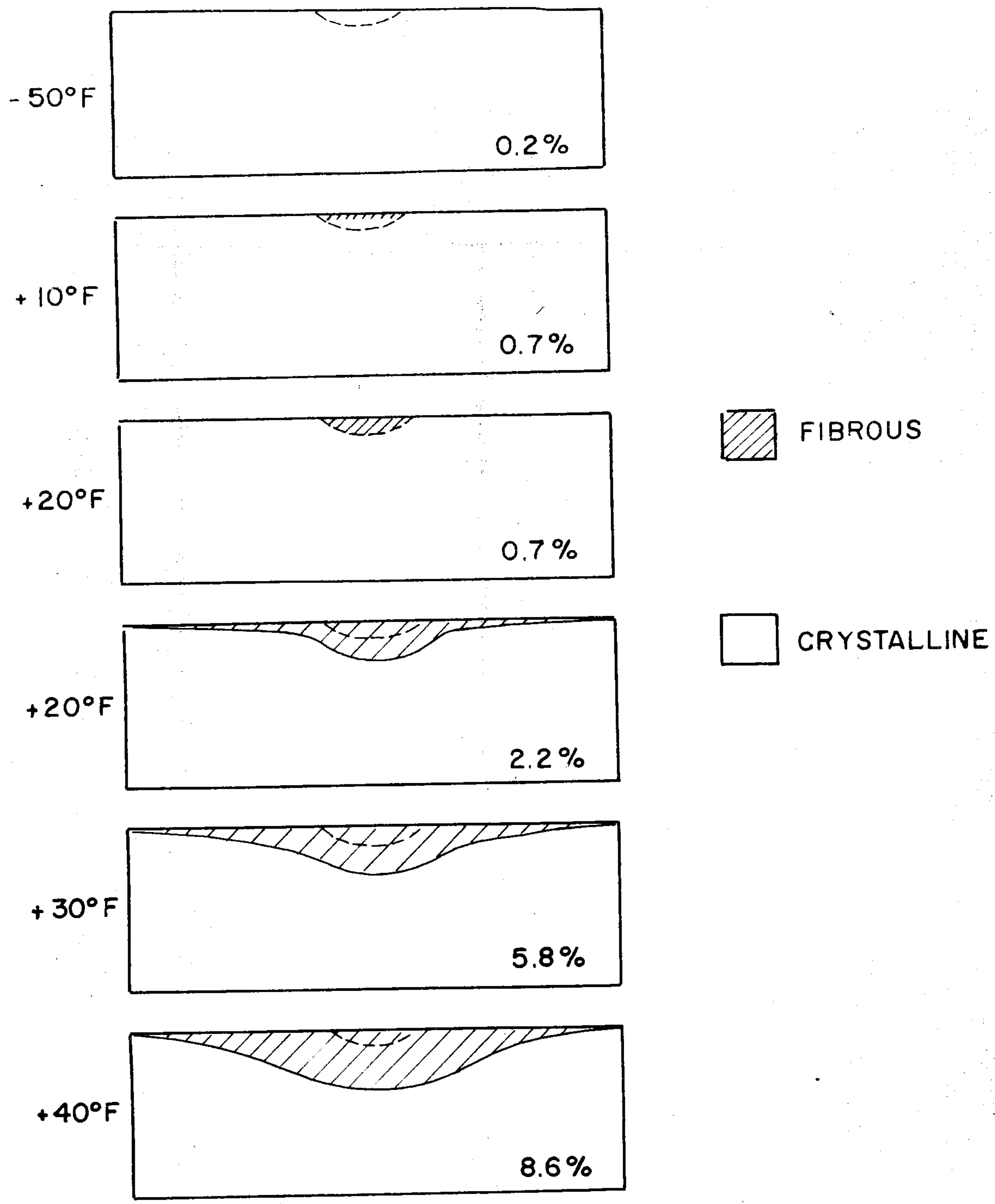


Figure 27. Fracture Behavior of Kinzel Specimens of A-201 Steel Welded with E7015 Electrodes.

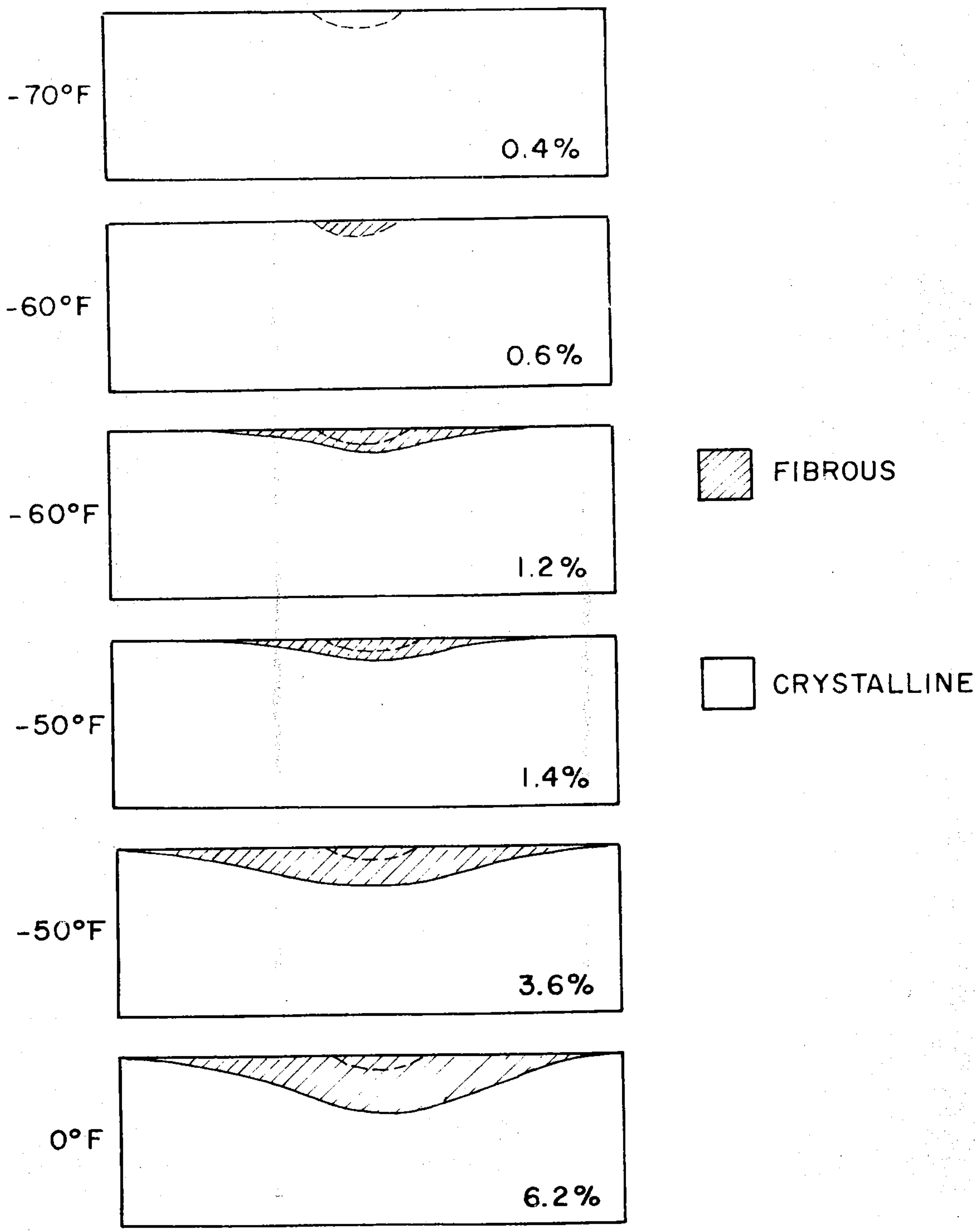


Figure 28. Fracture Behavior of Kinzel Specimens of A-201 Steel Welded with E6010 Electrodes and Postheated.

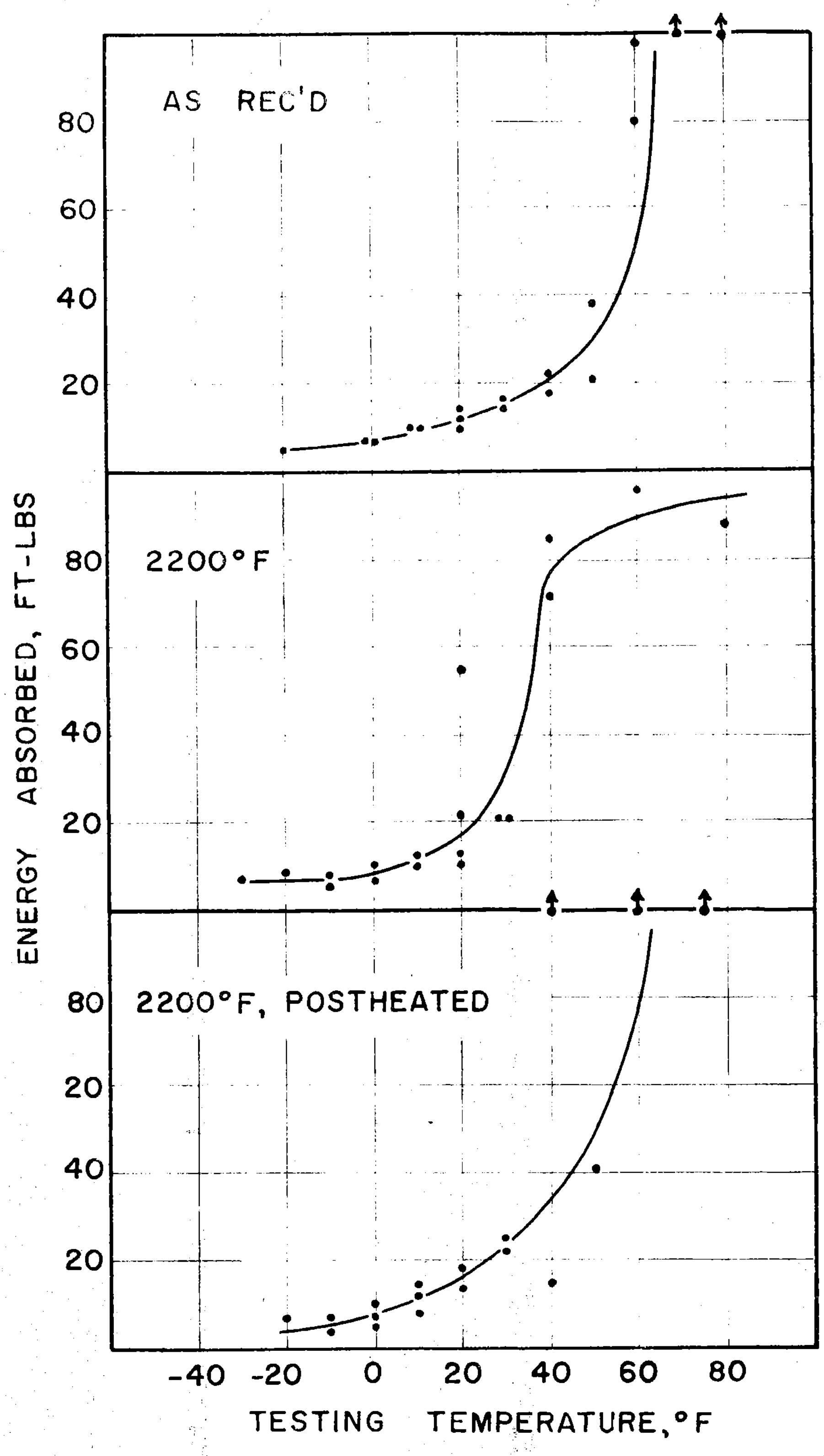


Figure 29. V-Notch Charpy Transition Curves for A-201 Steel in the As Received Condition and Heat Treated at 2200°F.

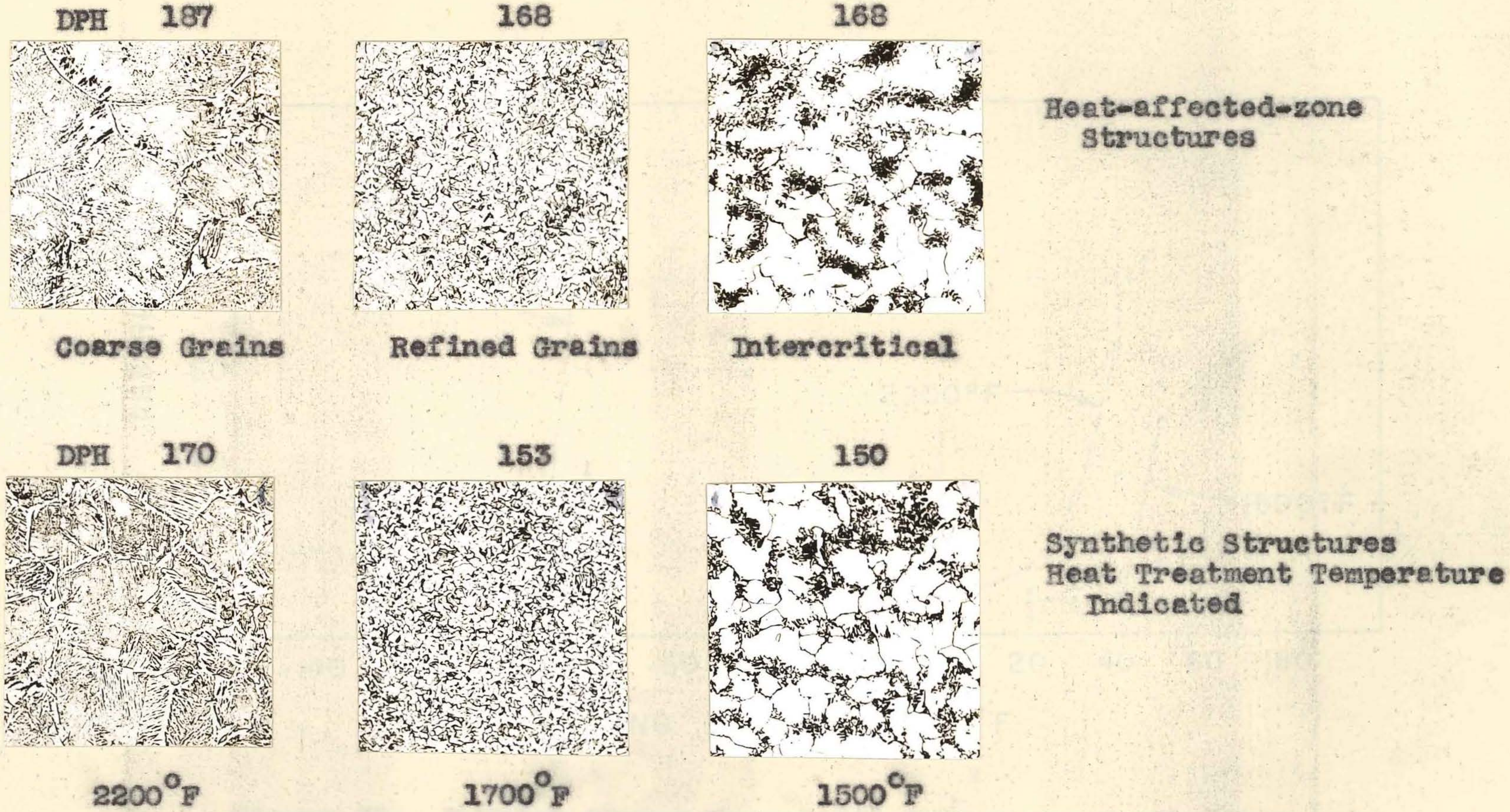


Figure 30. Comparison of Synthetic Structures with Actual Structures from the H.A.Z. of A-201 Steel. Picral Etch 100X. 10 Kg Diamond Pyramid Hardness also Shown.

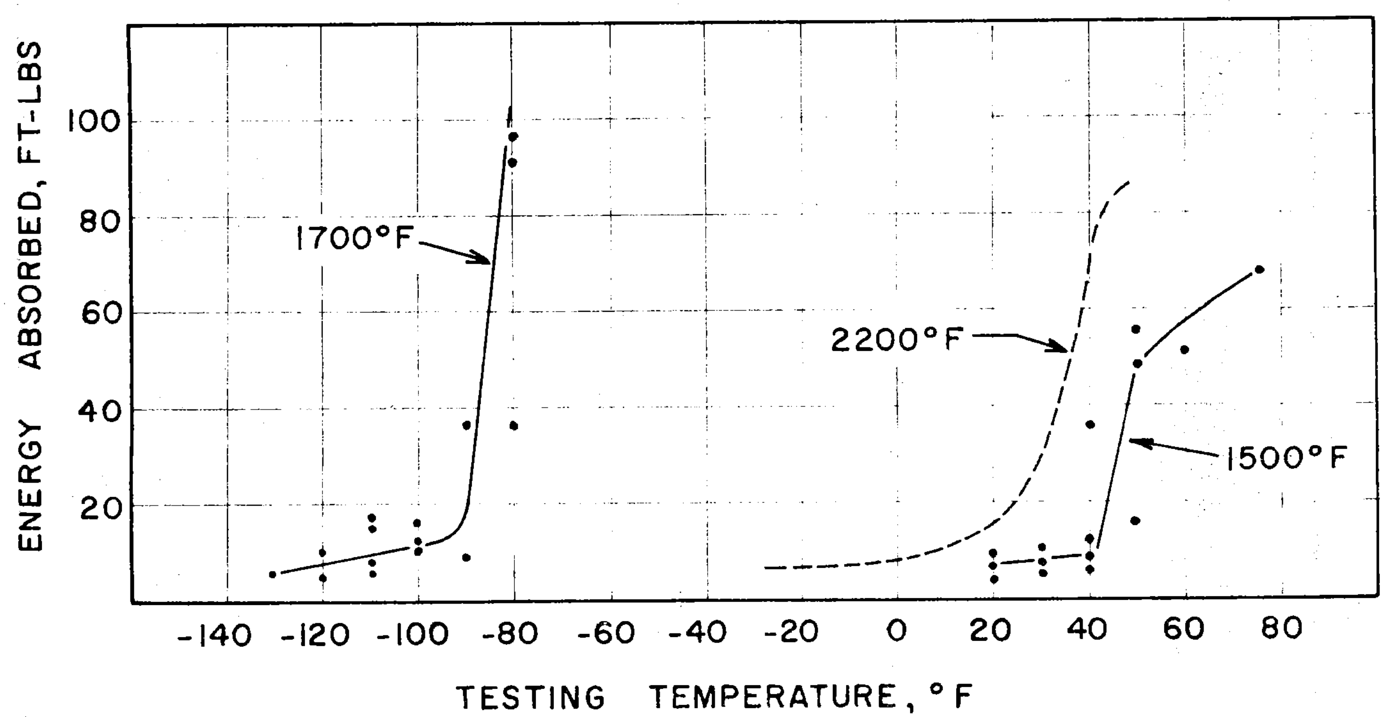


Figure 31. V-Notch Charpy Transition Curves for Synthetic H.A.Z. Structures of A-201 Steel.

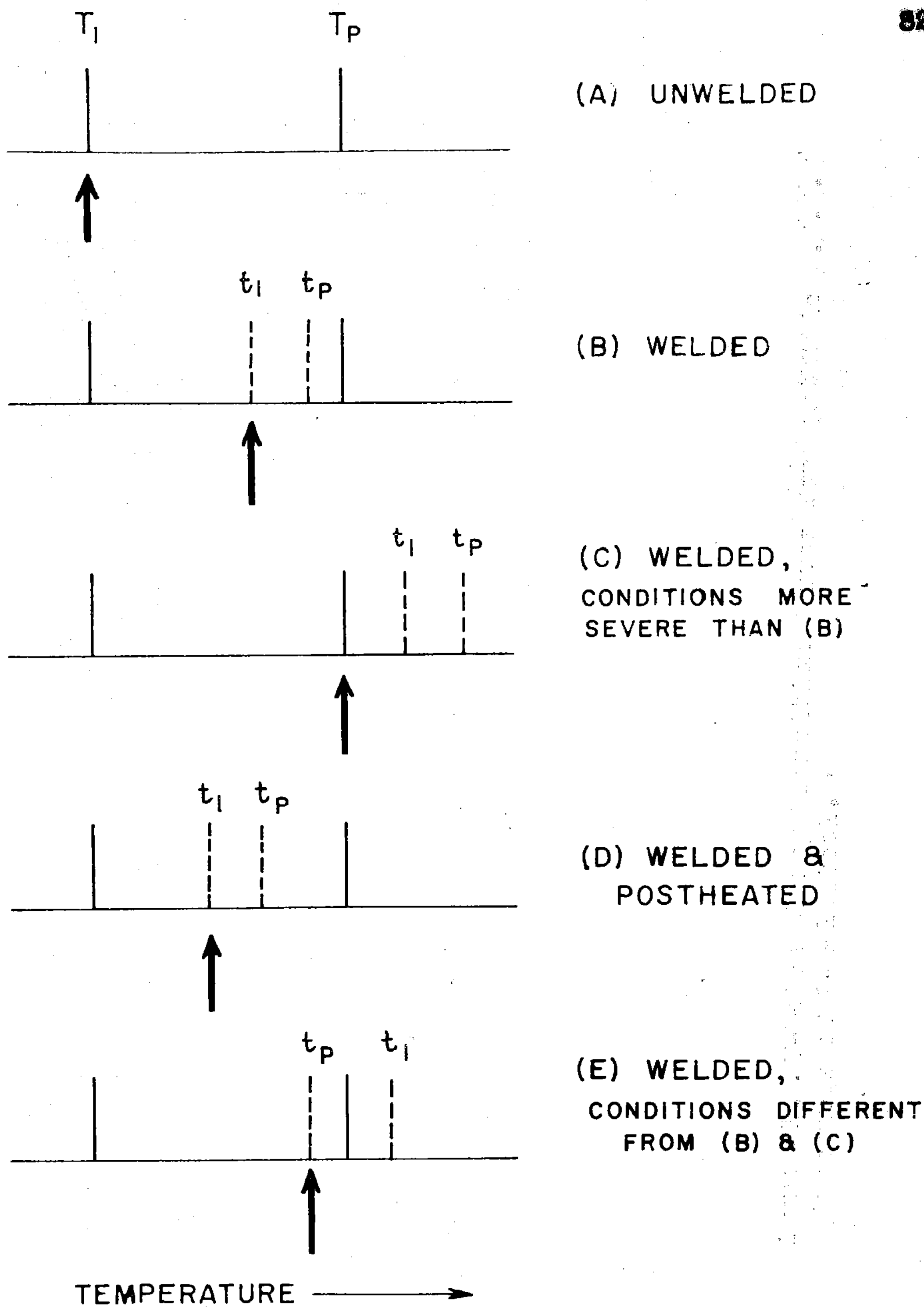


Figure 32. Schematic Diagram Showing How the Welded Kinzel Test Transition Temperature is Determined.

VITA

William James Murphy, the son of Kathryn G. and Leo T. Murphy, was born in Lansing, Michigan, on December 21, 1927. He graduated from Edwin Denby High School, Detroit, Michigan, in 1945, and received the degree of Bachelor of Science in Metallurgical Engineering from Wayne University, Detroit, Michigan, in 1949. In 1951 he received the degree of Master of Science in Metallurgical Engineering from Lehigh University. He was employed for one year by the General Electric Company, first on the Chemet Training Program and finally as metallurgist in the Thomson Laboratory, Lynn, Massachusetts. Since 1952 he has held the position of Instructor in Metallurgy at Lehigh University. In 1953 he married Dawn Elaine Phelan and they are parents of a daughter, Pamela Elaine.

The author holds memberships in Tau Beta Pi, Sigma Xi, The American Society for Metals and the American Welding Society. He has participated in the following publications:

1. Libsch, J. F., Chaung, W. P., and Murphy, W. J., "The Effect of Alloying Elements on the Transformation Characteristics of Induction Heated Steels," Trans., American Society for Metals, vol. 42, 121-146 (1950).

2. Rowady, E. P., Murphy, W. J., and Libsch, J. F., "Hardening Characteristics of Induction Heated Ductile Iron," Transactions of the American Foundryman's Society, 1952.

3. Murphy, W. J., and Stout, R. D., "Effect of Electrode Type in the Notch Slow-Bend Test," Welding Journal, vol. 33, no. 7, 305s to 310s (1954).